THE INSTITUTION OF PETROLEUM TECHNOLOGISTS.

THE ONE HUNDRED AND FORTY-FIRST GENERAL MEETING of the Institution of Petroleum Technologists was held at the House of the Royal Society of Arts, John Street, London, W.C. 2, on Tuesday, February 9th, 1932, Mr. James Kewley, M.A., F.I.C., President, occupying the Chair.

The Secretary read the names of the candidates nominated for election and the following list of members elected :—

As Members.—Hugh Logie Allan, Herbert Alfred Banks, William Munro Jennings, Spencer Geoffrey Oram.

As Associate Members.—Martin Louis Stewart, Oscar Weiss.

As Transference to Associate Members.—Heath Royden Hose, Hendrik Adriaan van Westen.

As Student.—William James Gillingham.

As Associate.—Edward William Bolton.

As Transference to Associate.—John Douglas Bing.

The President said that the author of the paper, Mr. Millar, was at the moment in Venezuela, and had written his paper on the field without the opportunity of referring to any libraries or books of reference, and that as the paper was being read a little earlier than the author had anticipated, he wished to reserve the right to make a few modifications later. Fortunately, Mr. C. A. Andrews, who had been working with Mr. Millar in Venezuela, happened to be in England, and although he ought to be in Germany he had kindly arranged to postpone his visit to that country in order to present the paper on behalf of the author.

The following paper was then read :—

Displacement Pumping as Applied to Oil Wells.

By ALBERT MILLAR, A.M.I.Mech.E. (Member).

THE evolution of production methods has been comparatively slow. Until "gas-lift" received the recognition it deserved, pumping, bailing and swabbing were the means universally used for lifting oil to the surface after wells had ceased to flow naturally.

During the past six years "gas-lift" has received much attention and study, and has developed into a most flexible method of producing. Its usefulness begins with the decline of natural flow and continues in the form of straight "gas-lift" until such time as, either the running pressure almost balances the rock pressure, or

the input gas to oil ratio becomes such that, for economical reasons, it has to be discontinued. In the ordinary course of events, wells would be put on the " beam " at this stage.

With the introduction of intermittent " gas-lift " the pumping period was still further postponed, and it was only natural that petroleum engineers would endeavour to find means for continuing to produce wells by compressed air or gas, when intermittent " gas-lift " proved to be no longer practicable or economical. Plant, such as compressors, pipe-lines, etc., etc., would continue to be available, having been installed for straight or intermittent " gas-lift," whereas additional capital outlay would become necessary if pumping equipment had to be provided. Well-balanced and efficient pumping equipment represents very considerable expenditure.

Displacement pumping by means of air, to raise large and small quantities of fluid over moderate lifts, has been practised for many years past. The ultimate outcome of much experimenting led to what is generally known as the " Displacement Pump," especially adapted for oil field work, the operating medium being either air or gas.

This method of lifting oil can be continued until the well has entirely exhausted itself, consequently, the pumping stage with its attendant evils of broken sucker rods, pulling for worn cups and working barrels, standing valve adjustments, etc., is altogether eliminated.

The importance of controlling production is becoming more widely appreciated, as it is realised that it is the means of obtaining the most efficient and economic utilisation of the natural energy in the oil sand; moreover, the ultimate recovery of oil from the sand is very considerably greater than would have been possible with old methods of exploitation.

In writing this paper it is the author's intention to deal with the more advanced life of producing wells, and he will endeavour to explain the most recent method of exploitation and the possibilities thereof, particularly as applied after wells have passed the " flowing " and normal " gas-lift " stages.

Let it be assumed that wells, having flowed under strict control and after showing indications of uneven flow, etc., but before ceasing to flow naturally, have been further exploited simultaneously by means of " gas-lift " in order to produce the maximum quantity of oil, whilst at the same time conserving the natural gas energy in the sand, and to have reached finally that stage when straight " gas-lift " proves no longer efficient or economical. At this stage a well is generally put on the pump, an unsatisfactory and by no means cheap method under certain conditions.

In the majority of cases it is at this period in the life of a well that careful control becomes most essential if the maximum quantity of oil is to be recovered from the sand, and it is precisely at this phase that control is difficult to maintain and is often relaxed altogether.

During the past three years, mechanical and electrical timing apparati to flow wells intermittently by air or gas have been devised and improved upon. The efficiencies of the results achieved have been remarkable. Production by these means is very flexible, and can be used with advantage during the advanced normal life of a "gas-lift" well, when, to lift a given volume of oil by continuous "gas-lift," an excessive volume of gas would be required, this necessarily resulting in low lifting efficiency.

With intermittent "gas-lift," the air or gas enters the well down the tubing and flows the oil up the annular space between the tubing and casing, although, in cases where the area of the annular space is less than that of the tubing the procedure is reversed. The number of intermittent flows the well makes is timed by mechanism operated either by mechanical or electrical means.

It has been proved that by substituting intermittent for straight "gas-lift" considerable economy can be effected in the amount of gas or air circulated per brl. of fluid lifted, whilst reducing the back-pressure on the sand; moreover, in most cases, this will result in increased production. This method usually has a tendency to increase the gas-oil ratio, therefore care must be exercised that increased production is not obtained at the expense of the formational gas to oil efficiency.

Whereas continuous "gas-lift" holds an almost unvarying pressure on the face of the sand, and the gas and oil are produced at a steady rate, intermittent "gas-lift" subjects the sand to pulsations of considerable magnitude. These pulsations have a maximum effect where the shoe of the tubing is set low, and will have an adverse influence on an open or loose sand, causing disintegration to take place. When it is realised that at each cycle there would be a reversal of flow, and at the time of maximum pressure, oil would be forced back into the sand, it is obvious that with the release of pressure—*i.e.*, when the "slug" of oil has been expelled—the flow of oil from the producing horizon to the well commences anew at increased velocity, causing the disintegration mentioned.

Therefore, to counteract partly the effect of these pulsations, it is advisable to set the tubing well above the producing sand. When it is known definitely that the sand being exploited is of open texture, the question of applying intermittent "gas-lift" must be given careful study, otherwise such damage might be sustained as would entirely off-set any gain in higher efficiency of circulated air or gas.

Following the success achieved by intermittent "gas-lift," the displacement pump, which is a unit possessing all the good qualities of intermittent "gas-lift" with none of its drawbacks, came into being.

Displacement pump.—The displacement pump consists of a chamber fitted with a standing valve in its lower end set in the well on tubing of 1½, 2, 2½, 3 or 3½ in. dia. Inside this tubing is lowered a second string of ½, ¾, 1, 1¼, 1½ or 2 in. dia., the lower end of which almost rests on the standing valve, or is, in some cases, directly attached to the valve itself.

The gas or air used to flow the oil passes down the annular space between the two tubing strings, and displaces the oil from the chamber up the smaller diameter tubing, referred to in this paper as the "riser tubing," known also as "eductor string," "flow tubing" or "macaroni" string. The "on" or "off" periods or cycles are regulated at the surface by a simple piece of electrical or mechanical equipment, similar in construction to that used with intermittent "gas-lift." A complete working cycle of the pump is divided into three stages :—

(*a*) *Filling period.*—Oil from the sand enters and fills the chamber through the standing valve.

(*b*) *Flowing period.*—The surface timing mechanism opens the main gas valve, thus allowing gas or air at pressure to enter the annular space, so displacing the oil into the "riser tubing," whence it is expelled.

(*c*) *Exhaust period.*—When the oil is expelled, the main gas valve is closed, and a second valve is operated which exhausts the air or gas. The pressure in the chamber and tubing now falls to atmospheric. With the beginning of the exhaust period, oil recommences to enter the chamber from the well.

It will be observed that the principles, on the whole, are the same as those governing the operation of intermittent "gas-lift," but the effects are very different. With the displacement pump the sand is not subjected to violent changes of pressure ; in fact, with wells having a fairly high fluid level, pulsations are almost non-existent at the sand face. Further, back pressure on the sand can be increased or lessened as desired, a most important point where a fine control of back pressure is to be maintained, as, for example, would be necessary where it is required to check water encroachment or the by-passing of gas in a case where gas-drive is in force.

Another advantage is, that where water and oil are being produced, little or no emulsification can take place ; whereas, producing with straight "gas-lift" and to a more or less extent with intermittent "gas-lift," emulsification results, and emulsions so formed are very difficult to break down.

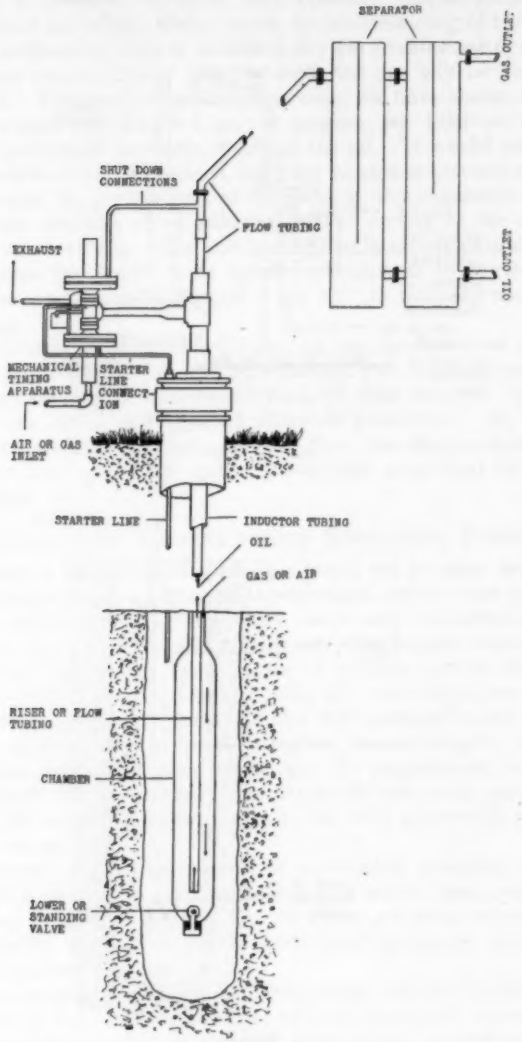

FIG. 1.

MECHANICALLY OPERATED DISPLACEMENT PUMP, WITH STARTER LINE.

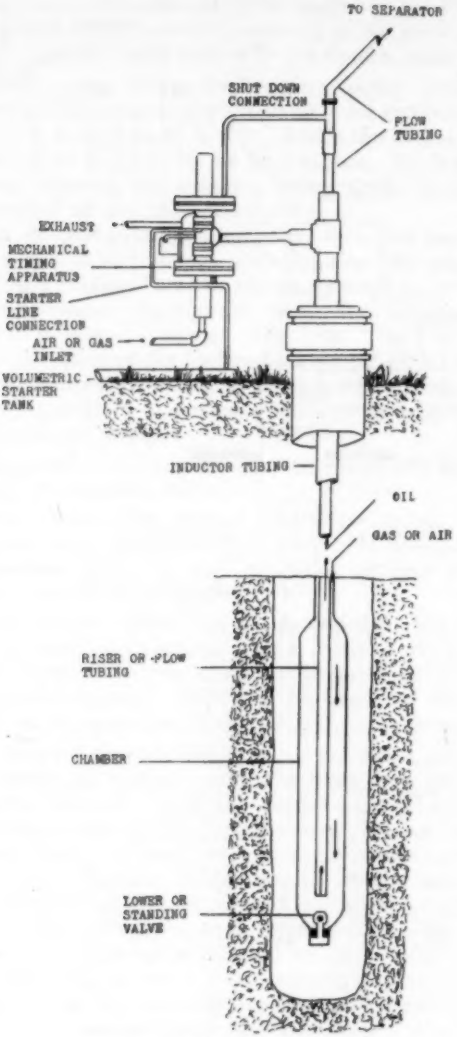

FIG. 2.

CHANICALLY OPERATED DISPLACEMENT PUMP, WITH VOLUMETRIC STARTER TANK.

With a properly designed and operated displacement pump using air or gas as the lifting agent, no intermingling of the oil and "lift" medium is possible, so that if dry gas (residue gas or stripped gas) from an absorbtion plant is used, the gas will be very little enriched. Experiments made when using air have shown that the air contained less than 0·5 gal. of gasoline per 1,000 cu. ft. after having performed its work of lifting the oil. It would seem that that portion of the air, which has been in closest contact with the oil, contains the greater part of the gasoline, the remainder enriches itself from the film of oil adhering to the surface of the chamber and "riser" tubing. The method of displacement pumping does not deplete the crude of its lighter constituents to anything like the same extent as does straight "gas-lift" or ordinary mechanical pumping.

The overall mechanical efficiency of the displacement pump is greater than that which can be obtained with intermittent "gas-lift" and still higher than that obtainable with straight "gas-lift" during the latter end of that stage of production. It is when compared with mechanical pumping that the displacement pump shows to best advantage and it is with this point that the author will mainly deal.

Displacement Pumping versus Mechanical Pumping.

Producing by means of a plunger pump set at some depth in a well is by no means an efficient arrangement, and in some cases, not at all satisfactory. Lifting costs vary very considerably with different types of wells and conditions. Mechanical obstacles due to difficult topography may hamper or entirely exclude the use of gang or central powers, crooked holes will cause excessive wear of sub-surface equipment, sand troubles will necessitate the frequent pulling of the pump in order to replace worn plungers, balls and seats, etc., etc. Gas interference may be experienced, especially where light oils containing from 20 to 40 per cent. gasoline, or wells with a high formational gas to oil ratio and low fluid levels, have to be pumped.

The most economical method of mechanical pumping is where 10 to 20 wells are operated by means of a central pumping power. This may be driven by gas or electric motor, or, where cheap power is available, electrically-driven individual pumping units may prove even more economical.

When using gang powers, the lifting costs may be anything from 10 to 40 U.S.A. cents per barrel of fluid produced, according to depth of well, quantity of oil lifted, sand, water, general conditions of the borehole and topography of terrain, etc. Where electrically or mechanically driven individual pumping units are used, the

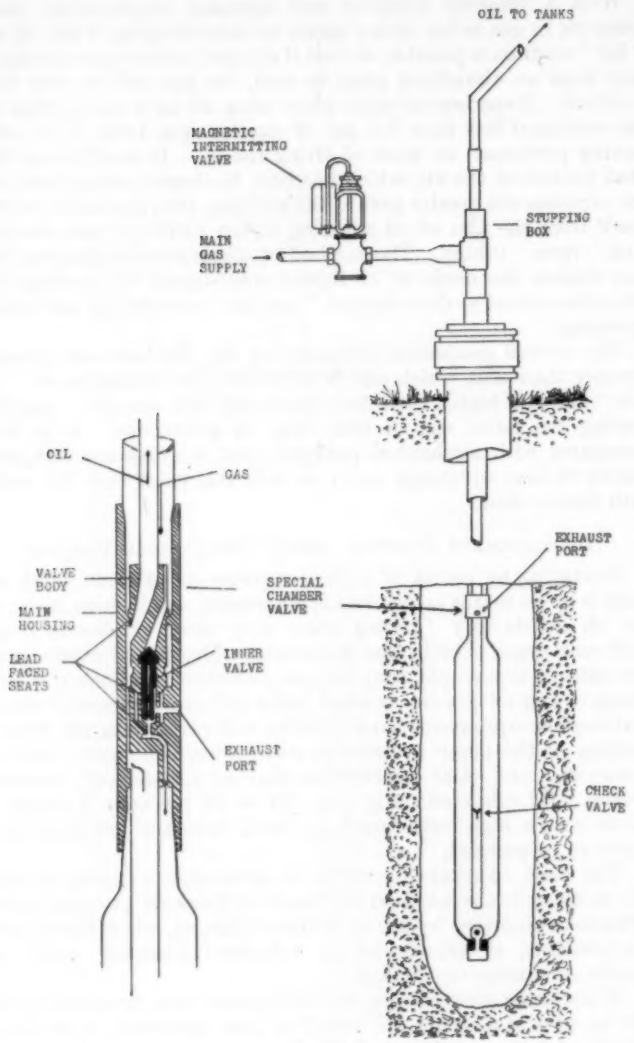

FIG. 3.

DISPLACEMENT PUMP WITH ELECTRICALLY OPERATED TIMING DEVICE.

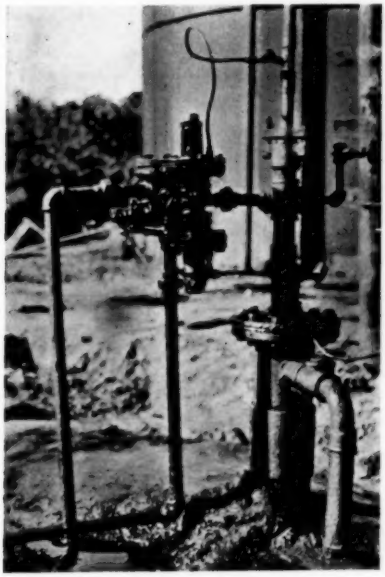

FIG. 4.

GAS OR AIR OPERATED MECHANICAL TIMING AND VALVE OPERATING DEVICE.

FIG. 5.

SAME AS FIG. 4, SHOWING VOLUMETRIC STARTER TANK.

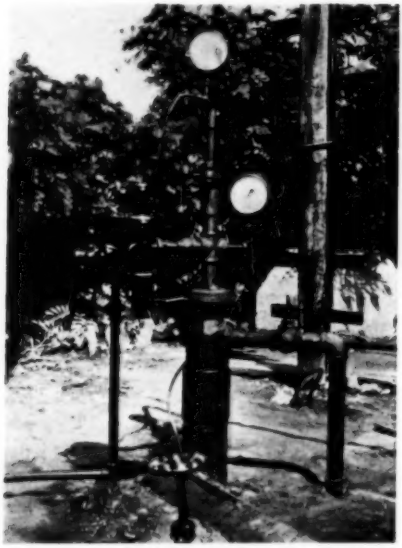

FIG. 6.

TIMING DEVICE SHOWING PRESSURE GAUGES AND SHUT DOWN CONNECTION.

FIG. 7.

TIMING DEVICE SHOWING STARTER TANK AND SCRUBBER TANK.

FIG. 8.

IDEAL SURFACE LAY-OUT FOR DISPLACEMENT PUMPING.

FIG. 9.

METERING AND DISTRIBUTING MANIFOLD.

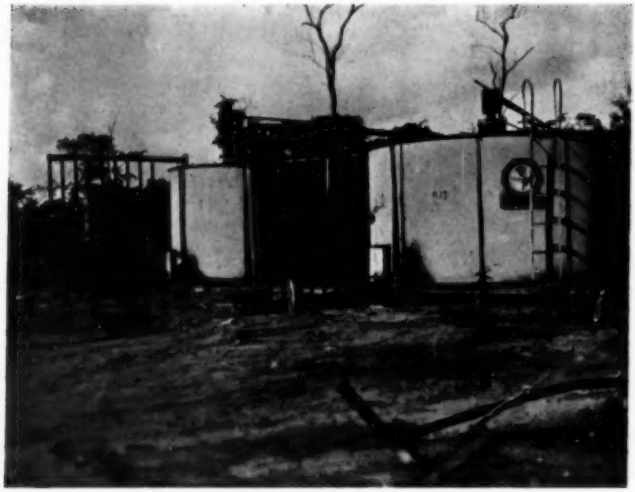

FIG. 10.

MAIN FLOW TANK WITH TEST TANK SHOWING OIL MANIFOLD.

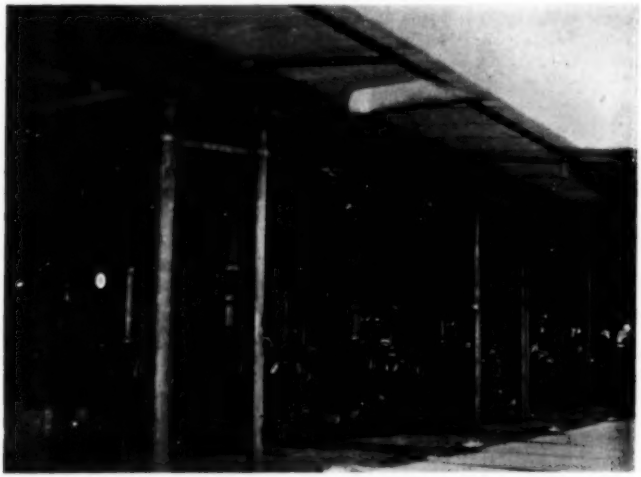

FIG. 11.

CENTRAL COMPRESSOR STATION USED FOR DISPLACEMENT PUMPING.

costs may be slightly less, for, there being an independent installation for each well, a higher pumping efficiency is attainable owing to the fact that the speed and length of stroke can be adjusted to suit any particular case.

The overall mechanical efficiency of the mechanically operated plunger pump, including sub-surface and surface equipment, can be as low as 4 per cent. and may be as high as 15 per cent. It is quite possible that higher efficiencies have been recorded, but they would be exceptional, and only obtained at a considerable expenditure of money, time and trouble.

Points in Favour of Displacement Pumping.

1. Easy to instal.
2. Suited to all kinds of topographical conditions.
3. Overcomes crooked hole and sand problems.
4. Reduces pulling costs.
5. Lessens emulsification of crude where water is being produced.
6. Facilitates control of water encroachment.
7. Alleviates production difficulties where crude contains paraffin.
8. It is as cheap, and in most cases cheaper, and more efficient than other mechanical means of producing.

The displacement pump is equally suitable for producing deep or shallow wells, the efficiency naturally being greater the shallower the wells. The same applies to mechanical pumping ; wells from 3000 to 5000 ft. deep, capable of producing up to 200 barrels per day, present a more difficult problem than those up to 2000 ft. deep.

The installation cost of an efficient plunger pumping unit is considerable and the upkeep costs high, in some cases being almost prohibitive due to subsurface mechanical trouble. When installing a displacement pump in wells over 2000 to 2500 ft. deep, consideration should be given as to whether an upper chamber valve should be fitted to conserve the air or gas under pressure in the annular space.

Topographical obstacles. — Difficult topographical conditions frequently present a serious problem when installing surface equipment. Such obstacles do not interfere in any way with the installation of a displacement pump, as all that is required to supply air or gas to a well is a small diameter pipeline, plus an electric cable, where magnetic valves are used.

The surface equipment is not only simple, but the expenditure on upkeep of the lines is practically nothing if they have been properly laid. The necessary pipelines will already be in existence where wells have previously been produced by means of " gas-lift."

To appreciate the advantage, one has only to compare the foregoing with the cost that would be entailed by the installation of jerk lines, line supports, swing posts, hold downs, multipliers, balances, butterflies, pumping powers and all the sundry surface equipment which is necessary when pumping from central powers. On the other hand, when individual pumping units driven by gas engine or electric motor are used, we have the multiplication of prime movers, gas and water lines, or electric transmission cables and transformers as well as other well head equipment.

Sand troubles. — Pumping wells making a lot of sand with consequent excessive wear of sub-surface equipment necessitating frequent pulling and loss of production, can be produced with minimum sand interference by the displacement pump. Not only can the chamber be set at a depth that will allow a column of liquid to be held continually on the oil-bearing strata, but the pressure in the annular space between the tubing and casing can be regulated to any desired extent, and in such manner that a minimum of pulsation can take place.

Particulars can be obtained from the daily production reports regarding the quantity of sand a well is making. If this information is used in conjunction with a study of the cores taken whilst drilling, initial production rates, pressures, gas-oil ratios, etc., a fair idea can be formed as to the existing condition of the sand. Such data will also be of assistance in deciding upon the rate at which the oil can be taken from the producing sand without causing excessive disintegration.

When dealing with troublesome sand wells, it is essential to keep as much back pressure as possible on the face of the producing sand, for by so doing the pressure differential through the sand to the hole is decreased and reduces the rapid expansion of gas in the sand and at the sand face, thereby lessening the tendency of a loose producing sand to disintegrate.

Of the two most generally known systems of displacement pumping, one has no sub-surface moving parts other than the standing valve, and if the ball and seat are raised from 6 to 9 in. above the bottom of the chamber, no trouble will be experienced through the sanding up of this valve. In exceptionally bad cases where sand is liable to collect in the bottom of the chamber, a device can be fitted to overcome this difficulty, and 2½ to 3 per cent. or even a higher percentage of sand can be handled with ease.

Crooked holes.—Wells which have been drilled "out of the vertical" are not only difficult to pump, but the cost of renewing sucker rods and tubing is a matter for serious consideration. In addition, there are the attendant risks of expensive fishing jobs

after parted rods and tubing and the loss of production while the well is being pulled. In very crooked holes, the casing is apt to become worn through as a result of the movement of the tubing which takes place during pumping. For such cases the displacement pump is found to be ideal, as it can be set without difficulty in the most crooked of holes as long as a 3-in. inserted joint chamber will pass down, and there is no fear of the tubing becoming damaged. The "off" production time will be cut by at least 90 per cent., owing to the fact that pulling and other maintenance work is automatically reduced. Crooked holes, which are the nightmare of the production man, can be exploited efficiently and without danger at very low cost.

Small diameter holes.—Small holes finished with 4½ in. casing or liner can be produced by means of the displacement pump if a 3-in. chamber is used.

Small producers.—Such wells can be handled with a percentage of efficiency similar to that attained in the larger ones. Wells 1000 to 2000 ft. deep, having low fluid levels of from 15 to 30 ft., and making from 4 to 15 barrels per day on the "beam" can be produced much more efficiently by displacement pumping.

Wells with low fluid levels usually present a difficult pumping problem. A well will not pump if there is much gas, for the reason that as the oil becomes agitated in the hole it becomes activated, or the well will pump "off" owing to the low fluid level. In either case the pump will become gas-bound.

In one particular instance which came under the author's notice, a well just over 1000 ft. deep, making a moderate amount of gas, could not be induced to pump, irrespective of the method of pumping adopted. Eventually it was decided to give displacement pumping a trial. The results achieved proved to be extraordinary, for, in spite of the fact that the running fluid level was below 15 ft., the well has been producing steadily at the rate of 18 barrels per day for nearly a year, and the lifting costs do not exceed 3 U.S.A. cents. per barrel.

In many cases, wells drilled into very tight sands and which are small producers yielding their oil very slowly but having a moderate fluid level, can be exploited advantageously by the displacement system to show a margin of profit. By this means they can be flowed a given number of times per hour or day, the number of flows being dependent on the rate at which the oil enters the well. Invariably it will be found that production can be increased.

Reduced pulling costs.—There is no need to emphasize the advantage to be gained by less pulling being needed. Pumping

wells, which require to be pulled every three or four weeks, for the purpose of making adjustments or to be cleaned, can be produced by the displacement pump for months without needing attention. The writer had experience with pumping wells which required pulling every two months on an average, either for the purpose of renewing valves and seats or to clean. These same wells have been produced uninterruptedly by displacement pumping for over eight months and are still in a satisfactory condition. In another case, a well had been producing for over eleven months before it was pulled, this being done more from curiosity than because it was necessary, and this experience is frequently the case.

Emulsion.—The displacement pump will give excellent results where wells have produced emulsified oil by straight "gas-lift" or by pumping. There is no intimate mixing of the oil and the propulsive element as is the case with straight "gas-lift," neither is there that turbulence which is caused by the plunger pump. The gas or air acts only upon the surface of the oil during displacement, and then lifts the column of oil displaced into the "riser" pipe in the form of a slug. As a consequence, very little intermingling takes place, and it has been the writer's experience that wells making emulsion when produced by other means can, in almost every case, *be produced emulsion free.*

If a number of wells making water have to be produced, it would be better to have a running pressure slightly in excess of that required under normal conditions, as this will assure a fairly high flow tubing velocity. Where a low running pressure and booster holes are used, the air or gas jetted into the "riser" tubing during displacement tends to effect emulsification in certain cases, if the oil and water being produced are in suitable proportions.

As the cost of treating an emulsified crude may be anything from 1·5 to 3 U.S.A. cents per barrel, this factor considerably affects production costs, especially these days when the margin of profit is low. The author had experience with one well in particular which produced by displacement pumping 60 to 80 barrels of oil and over 200 barrels of water every 24 hours, without any emulsion. The following figures obtained by actual field observation show how oil and water can be produced together without emulsification taking place :—

Well.	Emulsified oil production by straight "gas-lift" brls.	Emulsion content. %	Plus percentage of "free" water. %	Oil production by displacement pumping in brls.	Emulsion content. %	Free water produced. %
A.	31 brls. per day	30	20	50 brls. daily	Nil.	8
B.	12 ,, ,,	60	50	21 ,,	,,	15
C.	14 ,, ,,	15	20	20 ,,	,,	10

It will be observed that not only was the oil produced *emulsion free*, but the oil production actually increased by nearly 100 per cent. It will be noticed that up to 75 per cent. less water was produced, this being due to the fact that back pressure could be more efficiently maintained.

Water encroachment.—It becomes more difficult to cope with "edge" and "bottom" water problems as the field approaches the pumping stage. Back pressure can only be held when pumping by raising the pump and taking advantage of the static head so obtained, or by allowing the gas to build up a pressure in the casing annular space. This latter procedure is likely to cause trouble through the pump becoming gas-bound, especially in the case of wells with low fluid levels or those making large quantities of gas. As a general rule, control cannot be exercised effectively when using plunger pumps.

With the displacement pump, back pressure can be applied with excellent results to hold "edge" water in check. Water encroachment can be so controlled that "tonguing in" or "coning up" with the subsequent loss of oil so isolated in the sands, is reduced to the minimum.

Production engineers are realizing more and more that it is only by exercising the strictest control that the maximum quantity of oil can be recovered from the sands and the evils of rapid water encroachment curtailed. It is the author's opinion that the displacement pump provides the means of ensuring such control during that period of the life of a well when it becomes most essential, and this to a degree hitherto unattainable with ordinary pumping equipment.

Paraffinous crudes.—Wells producing crude containing a high percentage of paraffin often give trouble through paraffin precipitating in the tubing. This is attributable to various causes :—

(*a*) To gas expansion, which has a cooling effect.

(*b*) During drilling, to sand carrying comparatively cool water having been passed, the temperature of the water being considerably below that of the producing sand.

(*c*) In a case where production is obtained by means of straight "gas-lift" the input gas is sometimes introduced at a low temperature, for instance, this may occur during the winter months. The initial low temperature combined with a further decrease due to expansion of the gas, as well as the atomization of the oil which takes place during the flow up the "flow" tubing, will accelerate considerably the precipitation of paraffin.

(*d*) With pumping wells, owing to changed conditions in the producing sand and the oil. The latter contains less gas in solution and, of course, progresses upwards through the tubing at a low velocity.

The " riser " tube of the displacement pump is not liable to be affected seriously by any of the influences mentioned, and under ordinary working conditions, no paraffin will be precipitated in the tubing for the reason that :—

1. The formational gas does not assist in the lifting of the oil, therefore cooling from expansion is negligible.
2. Atomization does not take place as, already explained, the oil and propulsive medium do not intermingle, because the action of the displacement pump is that of a slug of oil moving at high velocity above a piston of air or gas.
3. The oil moves up the " riser " tubing at such a high velocity that very little of its original heat is lost through radiation.

In exceptionally bad cases where the paraffin content is above the average, pre-heated air or gas can be used with advantage. In passing down to the chamber, the pre-heated air or gas will warm up the " riser " tubing and so greatly assist in keeping it free of paraffin.

With highly paraffinous crudes such as have to be produced on some European oilfields, it would be advisable to keep the diameter of the " riser " tubing as small as possible in order to obtain maximum practical velocities.

No difficulties need be anticipated unless the crude contains an exceptionally high percentage of paraffin, as with moderate length slugs and velocities averaging 15 to 30 ft. per second, little or no paraffin will be deposited in the tubing.

Subsurface control when using gas-drive.—Taken as a general rule, the difficulty of controlling underground conditions increases as the wells and field get older, contributory causes being that the producing sands become more open and that channeling may have taken place if the wells were produced too rapidly during their early life. By the time that " the pumping stage " is reached, the question of control of gas-drive and water becomes increasingly acute, and to such an extent that it can be but partially dealt with when using ordinary pumping equipment.

With the displacement method of pumping, control can be exercised to within very fine limits, not only with respect to the volume of oil produced, but a consideration even more important is that back pressure on the sand can be maintained to within a few lbs. per sq. in. of the rock pressure, thus materially assisting in the prevention of channeling as well as holding water encroachment in check.

Water.—When water is present in a well, every endeavour should be made to trace its source of origin, it being an object of primary importance to produce as little water as possible. As a working figure it may be assumed that for every 1 per cent. of water contained in the crude, the specific gravity will increase by 0·0016. It follows that a high water content materially affects lifting costs, apart from any consideration of subsequent treatment of the crude.

If the water is found to be coming in from behind the water "shut-off" string, means must be taken to remedy any defect. In the case of "edge" or "bottom" water encroachment it might possibly be held in check by increasing the back pressure on the sand. Where the producing sand is of fair thickness a bottom hole seal or plug might be used with advantage in conjunction with maintained back pressure, where it is requisite to restrict the encroachment of the water. There are several ways by which back pressure can be applied :—

(*a*) By setting the chamber at such a depth that the oil column maintains back pressure.

(*b*) By regulating the flow of formational gas from the casing annular space so that a given pressure is constantly maintained.

(*c*) A combination of fluid plus gas back pressure can be used, this will be regulated to some extent by the position at which the gas enters the hole.

When back pressure is maintained by regulating the flow of formational gas from the casing head, it is advisable to use an extended gas anchor at the bottom of the chamber.

If a large proportion of the total quantity of fluid to be lifted is water, this fact must be taken into account, as it will have a direct bearing on chamber, tubing sizes, and running pressure.

In order to avoid emulsification when water is to be lifted with the oil, the crude should pass up the flow tubing at a velocity such that minimum intermingling with the air or gas takes place.

The most suitable velocity is dependent on the size of flow tubing, specific gravity of crude, viscosity, paraffin content, water content, etc. Here again the water may be fresh or salt or contain minerals in quantity, it may be finely divided or in large globules, and finally, it may contain clay or sand particles in suspension, any of these affecting the susceptibility to emulsification.

Where careful records of the water production can be kept, the results of any alteration in back pressure can be easily and effectively observed.

Factors Governing Dimension of Subsurface Equipment, Depth at Which Chamber Has to be Set and Conditions of Operation.

When contemplating the installation of a displacement pump, certain particulars have to be ascertained about the well :—

1. Depth of well.
2. Size of casing or liner.
3. Length of chamber.
4. Standing fluid level.
5. Running fluid level.
6. Potential production.
7. Formational gas-oil ratios.
8. Thickness and texture of sand.
9. Gravity and viscosity of crude.
10. Paraffin content.
11. Quantity of sand produced per unit quantity of oil.
12. Water production and origin.
13. Status relative to re-pressuring or gas-drive.

As is the case when solving other production problems, the greater the amount of reliable data available, the better the chance of initial success. It is most important to collect all possible data in order to be able to compare mechanical efficiency and lifting costs with former methods of producing.

Size of casing or liner and chamber.—The size of chamber will depend on diameter of casing or liner in the well. Chambers from 3 to 6 in. diameter are generally used.

Length of chamber.—Having come to a decision as to the diameter of the chamber and depth at which it is to be set, the next step is to decide its length. This is governed by :—

(*a*) Quantity of oil to be lifted per 24 hours.

(*b*) Number of cycles and displacements.

(*c*) Running pressure.

By dividing the number of cubic feet of fluid to be lifted by the number of displacements, the result will be the required capacity. To this figure 10 to 25 per cent. must be added to cover chamber losses which will vary according to conditions.

Definition of "chamber efficiency."—The ratio of total chamber capacity *minus* the chamber losses to the total chamber capacity is known as "the chamber efficiency." This may be expressed as :—

$$\frac{\text{T.C.C.—C.L.}}{\text{T.C.C.}} = \text{C.eff.}$$

(*a*) In some cases where back pressure has to be maintained the chamber efficiency is reduced. In order to ensure highest efficiency, the "riser" tubing or "macaroni" string should be set as close as possible to the bottom of the chamber, and where the formational gas-oil ratio is high, a gas anchor in the form of tubing run on the bottom of the chamber should be used. The efficiency of the chamber is also influenced by the height to which it is filled and the quantity of gas contained in solution in the crude.

(*b*) It is necessary to keep the number of cycles as low as possible, thus holding the input air or gas to oil ratio at a minimum, a factor which materially aids the maintaining of a high overall pumping efficiency.

(*c*) The running pressure is a governing factor in determining the length of chamber where any given sized riser tubing is used. Conversely, the diameter of the "riser" tubing chosen has a definite bearing on the length of chamber adopted. If the column of oil displaced from the chamber up the "riser" tubing has a static head equal to that of the running pressure, a state of equilibrium would result and the oil would not be ejected. Therefore, the total static head of contents of chamber, when displaced into the "riser" tubing, should be 10 to 50 lb. less than that of the running pressure, depending on prevailing conditions.

If a number of wells in one area are to be produced by means of displacement pumping, the wells must be surveyed to determine the required normal running pressure. For instance, particulars such as :—

1. Depth of wells.
2. Running fluid level.
3. Quantity of fluid to be produced.
4. Viscosity and specific gravity of crude.

In order to obtain the maximum production from wells having a low fluid level, a large number of cycles may be necessary, it therefore following that the lowest possible running pressure can be used. For example, if the cubic capacity of the annular space between the tubing *plus* that of the chamber and "riser pipe" is 10 cu. ft., and 100 cycles per day are necessary to obtain maximum production, approximately 10,000 cu. ft. of free air would have to be compressed were a running pressure of 150 lb. adopted. With

a running pressure of 200 lb. per sq. in. 14,250 cu. ft. would be required, whereas at a running pressure of 250 lb. approximately 17,700 cu. ft. will be used. By this it will be seen that if only 100 lb. running pressure were needed, running at 250 lb. would mean a decided drop in input oil to gas efficiency, resulting in increased lifting costs.

Although running pressure is the primary consideration, it may be directly influenced by adjustments of tubing combinations. The surface equipment must be taken into consideration when deciding upon running pressures. The higher the running pressure, the more units required to compress a given volume of air or gas, with consequent higher production costs. Pipework, fittings and valves must always be of the best quality and workmanship, and their cost increases considerably for pressures exceeding 250 lb. per sq. in.

Standing fluid level.—The height to which the fluid will rise will give, in some cases, a fair indication of the rock pressure. To check this and to ascertain gas conditions, a depth bomb (sometimes termed "pressure thief") should be run and a reading taken at 50–100 ft. intervals, starting from the top of the fluid column. If the oil column is gas cut, a low pressure reading will result. Where back pressure is to be held on the sand, the effect of this on the fluid level can be determined to some extent by running a depth bomb under like back pressure conditions.

Another very good reason for knowing the maximum height to which the oil will rise after the well has been inactive for a given time, is that, in the event of the well having to be shut down, the approximate "kick-off" pressure at which the well can be restarted will be known.

Running fluid level.—It is even more important to know this than to know the "maximum head." The "running fluid level" may be defined as the fluid level the well will maintain when producing the optimum quantity in a specified time. If accurate data is not available on this important point, it can be ascertained easily either by swabbing or bailing the well from a pre-determined depth, carefully noting meanwhile the amount of oil produced at each run and the time intervening between runs. The duration of this test depends on how long it must be repeated before the result of each consecutive run is practically equal.

Potential production.—The production from wells which have been producing at a steady rate on the "beam" can be increased by displacement pumping in nearly every case, because no ordinary plunger pump will produce the maximum quantity as efficiently.

Increased production can be expected from wells taken off straight or intermittent "gas-lift" and put on displacement pumping. It has been experienced that the production of wells making from 2 to 8 barrels per day by mechanical pumping has been increased by 300 to 400 per cent. when the displacement method was installed. Before running any subsurface equipment, it is essential to gauge the potential production as nearly as possible. The number of working cycles that will be necessary depends to a great extent on this information.

Formational gas-oil ratios.—Whatever quantity of gas is being produced by a well, it is essential to know from whence it comes. Is the gas coming in with the oil, or partly from the top of the sand, or in part from an upper sand? Having ascertained the source of the gas, the necessary back pressure to be held in order to produce the optimum quantity of oil with the lowest possible gas-oil ratio can be reasonably accurately estimated. This information will also decide the depth to which the tubing or gas anchor must extend below the bottom of the chamber to prevent gas interference, which tends to lessen chamber efficiency.

Thickness and texture of sand.—Information on this point can be obtained by referring to the drilling logs of the well in question, and geological reports and notes made in connection therewith.

Specific gravity and viscosity of crude.—The specific gravity must be known in order to calculate the running pressure, and the viscosity must also be taken into consideration. Comparing oils of high and low viscosity, shorter slugs of the former may be lifted without aeration or slippage, but the average velocity of slug in the "riser" tube must be less.

Re-pressuring or gas-drive.—If either or both of these methods of production are in operation, all available data must be taken into account to guard against channelling of the "drive medium." The depth at which the chamber is to be set must be arranged accordingly.

Sub-Surface Equipment.

Chamber construction.—The chamber can be constructed of standard collared casing or line pipe. Where the oil string or liner in a well is small and clearance limited, inserted joint casing can be used. It is always advisable to use seamless casing. Joints should be made up "tight," using a zinc lubricant. An arrangement can be fitted for the purpose of flushing out the sand trap around the standard valve during the displacement period, so that it may be effectively cleared of sand and other sediment.

Standing valve.—There are several types of chamber inlet or standing valves on the market, some of them being very elaborate. The writer's experience has been that the cheapest and simplest is an ordinary standing valve with renewable ball and seats, such as is used with the mechanical plunger pump. The standing valve is seated tightly in the shoe by means of a babbitted conical section. The chamber is lowered in, usually without the valve, which is either screwed on to the end of the "riser" tubing or connected to it by means of a "Garbut" rod which is lowered with the tubing. When it has reached its seat, it is raised and lowered once or twice to clear away any scale or sediment that may have collected, then finally seated and tapped tight, thus forming a perfect seal with the steel shoe. It is not practicable to use leather cups for this purpose.

Table No. I. has been compiled, giving the capacities of various length chambers constructed of standard sized pipe.

Tubing combinations.—The selection of the right size of tubing for the job is of paramount importance, because there are several conditions which have to be satisfactorily fulfilled if good results are to be obtained, for instance:—

1. Where running pressures exceeding 300 lb. per sq. in. are used, and the wells being exploited are over 2500 ft. deep, the tubing chosen should have a factor of safety of 2½. For lower working pressures and shallower wells a factor of safety of 2 may be used, but 2½ is preferable. If the standing valve is connected to the "riser" tubing without a "Garbut" rod, it is quite possible that the outer or "inductor" tubing will be carrying a portion of the weight of the flow tubing.

2. During the working cycle the tubing is subjected to stresses occasioned by the "impact" shock, and it is on this account that it is advisable to use a factor of safety of 2½ or even 3. This shock is caused by the sudden rush of air or gas into the annular space between the flow tubing following the instantaneous opening of the main valve, and is greater when the annular space is at atmospheric and the running pressures are high.

It has been recorded that in the wells with the chamber set at approximately 1000 ft. below the surface, the time taken to raise the pressure in the annular space from 0 lb. to 150 lb. per sq. in. gauge was 1½ to 2 seconds, whereas in wells approximately 2500 ft. deep it took from 8 to 18 seconds to raise the pressure from 0 lb. to 500 or 700 lb. per sq. in. depending on the area of the annular

TABLE I.

Chamber Capacities in Cubic Feet.

Chamber dimensions. Size.	Inside dia.	Outside dia. of collar.	Length in feet. 1	10	15	20	30	40	50	60	70	80	90	100	
in.	in.	in.													Remarks.
3	2·750	3·628	0·041	0·41	0·615	0·82	1·23	1·64	2·05	2·46	2·87	3·28	3·69	4·1	3in. inserted joint casing for use in 4½in. liner.
3½	3·000	3·878	0·049	0·49	0·735	0·98	1·47	1·96	2·45	2·94	3·43	3·92	4·41	4·9	3½in. inserted joint casing for use in 4½in. liners.
4	4·02	5·091	0·087	0·87	1·305	1·74	2·61	3·48	4·35	5·22	6·09	6·96	7·83	8·7	4in. line pipe for use in 6½in. casing or liners.
4½	4·49	5·491	0·110	1·10	1·65	2·20	3·30	4·40	5·50	6·60	7·70	8·80	9·90	11·0	4½in. casing for use in 6½in. casing.
6½	6·049	7·390	0·199	1·99	2·98	3·98	5·97	7·96	9·95	11·94	13·93	15·92	17·91	19·9	6½in. for use in 8½ casing.

TABLE II.

Size. in.	Outside dia. in.	Inside dia. in.	Outside dia. collar. in.	Weight per ft. lb.	Setting depth in feet Factor of safety. 3	2½	2	Internal cross sectional area in sq. ft.	Length of pipe containing 1 cu. ft. ft.	Tubing combination.	Cross sectional area of annular space in sq. ft.
¼*	0·840	0·546	1·024	1·09	2000	—	—	0·0016	615	¼ "in 1¼"	0·00655
⅜*	1·050	0·742	1·281	1·473	2200	—	—	0·0031	333	⅜" in 1¼"	0·0081
	1·315	1·049	1·576	1·684	2400	—	—	0·0060	—	1" in 2"	0·0122
1*	1·315	0·957	—	2·171	2500	—	—	0·0050	—	—	—
1¼	1·660	1·380	2·054 or	2·300	2651	3181	3976	—	—	—	—
	External Upset		2·200	2·400	5571	6685	8356	0·0104	96·27	1¼" in 2¼"	0·0175
1½	1·900	1·610	2·169 or	2·750 or	2759	3311	4139	0·0141	70·7	1¼" in 2¼"	0·0129
	External Upset		2·500	2·900	5710	6852	8565	—	—	1¼" in 3"	0·0291
2	2·375	1·995	2·870 or	4·600 or	3379	4055	5068	0·0216	46·4	2" in 3"	0·0180
	External Upset		3·060	4·700	5670	6804	8506	—	—	2" in 3½"	0·0349
2½	2·875	2·441	3·517 or	6·400	3644	4373	5466	0·0325	30	—	—
	External Upset		3·668	6·500	5662	6795	8493	—	—	—	—
3	3·500	2·992	4·200 or	9·200	4000	4900	6000	0·0487	25·6	—	—
	External Upset		4·504	9·300	5500	6600	8300	—	—	—	—
3½	4·000 or	3·548 or	4·750	9·500	3000	3600	4500	0·0684	14·56	—	—
	4·000	3·476	5·000	11·000	3400	4000	4600	0·0656	15·5	—	—

* Extra strong pipe.

NOTE.—Owing to the possibility of defects, ¼in., ⅜in. and 1in. should only be run with a safety factor of 3.

space and reservoir capacity of surface lines, etc. From this information it is very evident that considerable shock is transmitted to the tubing.

Even assuming that the oil level in the chamber commences to fall proportionately with the rise in pressure, thereby creating a cushioning effect, the fact still remains that very considerable shock will be experienced. The application of the running pressure is so sudden that its effect can be likened to that of an "impact" and can be compared with that occasioned when suddenly opening a valve at the boiler end of a long steam line, whilst the valve at the opposite end is only partially opened.

To what extent this "impact" shock is absorbed by the oil remains problematical, for, if it is assumed that 4 cu. ft. of liquid is displaced from a 4-in. dia. chamber 50 ft. long up a riser tube 1¼-in. dia. in three seconds, the average velocity of the downward moving column of oil would be 16·6 ft. per second and the average velocity of the displaced fluid up the "riser" tubing would be 128 ft. per second, a figure which in all probability is exceeded in practice.

Table No. II is given with the object of rendering more easy the determination of the size of tubing most suitable for any particular case. The factors of safety have been in some cases taken from the maker's catalogue or deduced for the purpose. Wherever possible seamless tubing should be used.

Tubing Combinations.

Induction tubing.—The selection of this tubing depends entirely on the "riser" tubing, and should be such that the area of the annular space be kept as small as is practically possible, especially when chamber valve devices are not used, in which case the total volume of air-gas is exhausted at each cycle. In practice it would seem that good results are obtained with the area of the annular space the same, or even slightly less than, the internal area of the "riser" tubing.

"Riser" or flow tubing.—The diameter of the "riser" tubing is dependent on the following factors :—

(*a*) Running pressure available.

(*b*) Quantity of fluid to be lifted per cycle.

(*c*) Depth of well, etc., etc.

Table No. III has been compiled to facilitate the selection of the most efficient-sized tubing to lift the maximum quantity of fluid with the minimum volume of air or gas at a reasonable running

TABLE III.

Cubic Feet Displaced from Chamber Up Flow String. Working Pressure in Chamber for Various Volumes Displaced and Sizes of Flow Tubing. Specific Gravity of Fluid = 1·00. Average Velocity of Flow 25ft. per sec.

Size.		½ cu. ft.	¾ cu. ft.	¾ cu. ft.	1 cu. ft.	1½ cu. ft.	2 cu. ft.	2½ cu. ft.	3 cu. ft.	4 cu. ft.	5 cu. ft.	6 cu. ft.	7 cu. ft.	8 cu. ft.
¾in. in 1¼in.	Fluid column	153·7	307·5	461	615	922·5	1230	—	—	—	—	—	—	—
	Working pressure lb. sq. in.	75	142	208	280	410	540	—	—	—	—	—	—	—
	Cu. ft. free air required per cycle	54	88	130	175	273	376	—	—	—	—	—	—	—
¾in. in 1½in.	Fluid column	83·3	166·6	249·9	333	499·6	666	832·6	999	—	—	—	—	—
	Working pressure lb. sq. in.	44	80	116	152	224	296	368	440	—	—	—	—	—
	Cu. ft. free air required per cycle	46	74	105	135	203	274	350	430	—	—	—	—	—
1in. in 2in.	Fluid column	41·6	83·3	124·8	166·6	249·9	333·2	416·5	499·8	666·4	833	—	—	—
	Working pressure lb. sq. in.	—	44	61	80	116	152	188	224	296	368	—	—	—
	Cu. ft. free air required per cycle	—	73	97	121	170	225	280	337	460	592	—	—	—
1¼in. in 2½in.	Fluid column	—	48	72	96·2	144	192·4	240	288·6	384·8	481	577	672	—
	Working pressure lb. sq. in.	—	—	40	51	72	93	115	136	176	218	260	300	—
	Cu. ft. free air required per cycle	—	—	105	127	170	215	265	309	405	510	620	732	—
1½in. in 2½in.	Fluid column	—	—	53	70·7	106	142	177	213	284	355	426	497	568
	Working pressure lb. sq. in.	—	—	—	40	55	75	90	100	135	163	194	225	255
	Cu. ft. free air required per cycle	—	—	—	104	133	174	206	231	310	380	459	543	630
2in. in 3in.	Fluid column	—	—	—	46·4	69	92	115	138	184	230	276	322	368
	Working pressure lb. sq. in.	—	—	—	—	40	50	60	70	88	108	130	150	170
	Cu. ft. free air required per cycle	—	—	—	—	152	179	211	241	299	366	440	512	587

In practice it will be found that those values to the left of the heavy line will not give such good results as the oil column is not of sufficient length to stop penetration.

NOTE.—The cubic feet of free air has been calculated on tubing combinations 1000ft. long.

pressure, but as previously mentioned, factors such as sand, water, paraffin, viscosity and specific gravity play an important part, and have therefore to be taken into account.

Another point is the minimum length of slug that can be lifted without undue aeration or slippage. The maximum length of slug is limited by the working pressure; the minimum length permissible is that which will remain a compact column of unaerated oil above the expelling medium. Mr. C. S. Baird, in his article on "Slug Flow Experiments," gives the minimum ratio of length of oil column to length of lift as follows :—

Length of "lift."		Length of column.
1000ft.	..	150ft.
2000ft.	..	175ft.
3000ft.	..	200ft.
4000ft.	..	250ft.
5000ft.	..	400ft.

Running pressure.—It will be noticed that the running pressures given in Table No. III are only very slightly higher than the static head of the column of oil displaced into the "riser" tubing, and, at first sight, this might be thought to be an error. It is quite possible that unless very careful consideration is given to this point a running pressure will be adopted in excess of that which the occasion demands, a proceeding which will result in decreased input air or gas to oil efficiency. Investigations show that the velocity head required to set in motion the oil to be lifted is not very great. The oil is displaced successively; in other words, the static head of the oil column is progressive and, as already remarked, the initial velocity of the oil is very high owing to the "impact" pressure of the propulsive medium. The friction head of the oil column is a minor detail which need not be taken into account. The friction head due to the flowing of the gas or air up the riser tubing is also very small, because the pressure differential through the "riser" tubing during the lifting period remains practically constant, as very little expansion of air or gas occurs owing to the fact that the inlet valve is not closed before the upper end of the slug has reached the surface. As a general rule it can be accepted that for the lifting of every 100 ft. of slug, a running pressure of from 40 to 50 lb. per sq. in. will be required, small variations being dependant on water conditions, viscosity of oil, specific gravity, etc., etc.

Position of "booster" orifice in flow tubing.—Where the oil sand is capable of giving a higher yield than that already being exploited, production can be increased either by speeding up the number of cycles or by lifting a greater volume of oil at each cycle.

When the available running pressure is barely sufficient to lift a given quantity of oil, the velocity of the flow will be so retarded that excessive slippage is likely to occur. In order to overcome this trouble by a method other than changing the chamber capacity or size of flow tubing, a "booster" orifice can be drilled in that section of the flow tubing situated in the chamber. The effect of this orifice in the flow tubing is important, for when the fluid level in the chamber is depressed to that of the orifice, a jet of air enters the rising column of oil, which consequently becomes aerated. This materially assists the "lift" by increasing the velocity, which, in turn, will speed up the number of cycles and so increase production.

Where the running pressure and size of flow tubing are such that the maximum production cannot be obtained, the use of a "booster" hole will permit of the chamber being enlarged from 10 to 15 per cent. or more, so giving a correspondingly greater volume per cycle.

If the orifice is located too high, excessive aeration and even slippage will take place, this giving rise to an increased air or gas to oil ratio; conversely, if placed too low, the beneficial effect of the orifice will be to a large extent nullified.

Experiments have shown that a "booster" orifice is most satisfactory when placed from 30 to 50 per cent. of the distance measured from the bottom of the flow tubing to the top of the chamber. One method of solving this problem is to calculate the volume of oil which, when displaced from the chamber and standing in the flow tubing, will represent a static head equivalent to 65 to 70 per cent. of the running pressure. When this volume has been displaced, the oil in the chamber will have been reduced to a new level, and at this point the orifice holes should be situated.

The size of "booster" orifice may be $\frac{1}{16}$ in. to $\frac{1}{4}$ in. and it would seem in practice that two small holes are better than one large one of equal cross sectional area.

It is usual to place the orifices in a collar and they should be drilled at an angle of 60° so that the jet of air impinges diagonally on the axis of the rising column of oil.

Flowing time velocity.—The total flowing period can be taken as from the opening of the inlet air or gas valve to the arrival of the column of oil, called the "slug," at the surface. This period can be divided into two parts:—

(*a*) That in which the oil is being displaced from the chamber and propelled up the "riser" tubing.

(*b*) The time taken for the oil, now totally displaced from the chamber, to arrive at the surface.

The time taken to displace the oil from the chamber varies between 1 and 8 seconds, being dependent on capacity of chamber, depth at which it is set, and the time necessary to raise the pressure in the annular space to that of the running pressure.

The average velocity of the "slug" of oil is controlled by the static head of the column and the working pressure. If the chamber is completely filled each cycle, the average velocity of the oil column will be the height measured from the top of the chamber to the point of entry into the separator, divided by the time of flow in seconds. Average velocities from 7 to 45 ft. per second have been observed.

The initial velocity at which the oil is displaced is of importance, and is governed to some extent by the pressure in excess of that required to balance the static head equivalent to the displaced column of oil and to the dampening of the impact effect on the surface of the oil due to the high velocity of the incoming air or gas being restricted in its flow down the annular space.

The higher the initial velocity, the sooner the inlet valve may be closed and more advantage taken of the expansion of the air or gas to flow the column of oil to the surface. With natural flow and straight gas-lift, velocities below five or six feet per second are not practicable and this also applies to displacement pumping.

When the velocities fall below six feet per second, the action will be no longer that of a solid column of oil above a column of gas, but a series of small columns made up respectively of oil, gas and oil and gas. With low velocities the oil will have a tendency to fall back through the gas column.

Where excessive velocities are attained, or, in other words, if the running pressure is far in excess of that actually required to raise the oil, the gas will tend to break through the oil column with the result that the rising slug will become an oil and gas mixture, similar to that experienced with "gas-lift." Practice indicates that with shallow wells from 1000 to 3000 ft. deep, velocities of from 10 to 30 ft. per second are permissible. With wells 3000 to 5000 ft. deep, 8 to 25 ft. per second is found to be more appropriate, this depending to a large extent on the length of the oil column.

As there are so many factors which influence velocities, it is difficult to lay down any hard and fast rule. The most suitable velocity is that which will lift a slug of oil to the surface with the greatest volumetric efficiency and minimum aeration.

Surface Equipment.

Pipelines.—The pressure air or gas lines to the wells may be of 1¼, 1½ or 2 in. dia. standard line pipe. The size of lines to be used is controlled by the volume of air or gas required per cycle,

and should be such that the drop in pressure when air is being admitted to the well is as small as possible.

The use of oversized pressure lines is a good rather than a bad feature, as they act as accumulators and so assist in keeping the pressure in the system more or less uniform. In fact, it is good practice to construct the dirt and moisture trap at the well site, giving it a capacity of from 3 to 4 cu. ft.

All surface pipelines should be protected from possible rupture by uncertain terrain conditions, road traffic, debris in streams and sagging in hollows, as a ruptured line will in most cases shut down all the wells in a system.

In countries having temperate and cold climates the lines should be buried at a reasonable depth, care being taken to see that all lines are thoroughly tested after being laid in the ditch. No matter what type of valve mechanism is used at the well, a dust and moisture extractor is indispensable and must be fitted in the line as close to the main valve as possible, for it has been found that moisture, millscale and dust cause more inconvenience than any other operating hazard. The extractor, or, as it is sometimes called, "separator," is usually made from a section of old casing 14 to 18 in. dia. from 3 ft. to 3 ft. 6 in. long, with the necessary internal baffles. In order to arrest more efficiently particles of dust and scale, it is good practice to allow 3 or 4 in. of oil to be carried in the bottom of the separator. Facilities should be provided for the draining and cleaning of the separator at regular intervals.

Gas-traps.—Although in accordance with good practice the installation of a gas trap is advocated, it can be dispensed with, but in that case the flow line and tanks would be subjected to considerable strain. The slug of oil moves at high velocity, as does also the air or gas following. When the latter leaves the flow tubing it expands rapidly, and if two or more wells happen to flow into the storage tank simultaneously, then there is every possibility of the roof of the tank becoming severely strained or, in extreme cases, damaged.

Again, if the flow tanks are connected to a vapour recovery system, large volumes of air entering the tanks would dilute the gas and vapours, so that by using a trap at the wellhead, the air or dry gas can be separated, leaving the vapours from the tanks *plus* the rich casing-head gases to be collected for gasoline recovery.

Moisture.—In places where the humidity is high it may be found necessary to use an "after cooler" to remove the excessive moisture that would otherwise collect in the lines to be carried forward in slug form. This slug, on reaching the timing mechanism, may cause serious damage and a temporary shut down of the well.

Pre-heating. Air or gas.—Any of the conventional air-heating devices may be used for heating the air before its entry into the well. If several wells are situated in close proximity one to another, a single central heater could be used with " thermó " control.

Pressure and cycle control.—It is not obligatory to have a recording pressure gauge at each well, but if high efficiencies are to be maintained a recording pressure gauge with a one-hour clock is necessary. This can be moved from one well to another, and should be used daily in order to check the cycles and their periods.

Sub-surface control of the cycle.—The control of the cycle is accomplished by means of timing apparatus either electrically or mechanically operated. In the former the main inlet magnetic valve can be controlled either at the gas or air distributing manifold or at the wellhead. The mechanical timing device is operated by the compressed air or gas used to lift the oil.

The simplest automatic timing of the cycle using the mechanically operated valve is obtained by the means of a small receiver. Air is allowed to pass into this through a small orifice, and pressure is gradually built up so that at a given time and pressure it operates the main valve of the apparatus. The starting pressure ranges from 3 to 20 lb. or more, depending on the length of the cycle. The starting chamber or reservoir is evacuated to atmospheric pressure each cycle at the exhaust period.

Volume control, air or gas.—The total volume of air or gas being delivered from the compressor plant should be metered, thereby enabling a control to be exercised over the volume output of the compressors, which volume, when checked against that required for the running of all the displacement pumps in operation in that particular system, will facilitate the location of serious leakages.

Volume control of production.—In order to know with what efficiency the displacement pump is functioning, it is imperative that it be possible to measure the volume of liquid produced at each cycle or over a given number of cycles collectively. For small producers a 20 barrel tank is ample. If a number of wells are being pumped in one area, then a central collecting tank of 100, 250 or 500 barrels capacity in conjunction with a test tank of 20 to 30 barrels capacity can be used with advantage, the flow lines in this case being manifolded in such a manner that the production of any individual well can be switched to the test tank for observation. By so measuring the production, it is not only possible to check accurately liquid volumetric efficiency, but also the percentage of water, if any, that is being lifted, and back pressure if used can be adjusted as required.

Efficiency Details of the System.

The efficiency of operating the displacement pump can be divided into three parts, viz. :—

1. Chamber volumetric efficiency.
2. Tubing efficiency.
3. Surface equipment efficiency.

The chamber efficiency can vary very considerably, and is seldom higher than 85 per cent. Excessive loss of efficiency, which is controllable in most cases, is generally due to one or more of the following causes :—

Cause.	Remedy.
(*a*) Chamber being too large for the capacity of the well.	*Reduce size of chamber.*
(*b*) Chamber set too high in the first place, or lowering of the running fluid level.	*Lower the chamber so that the level of the fluid rises to the top of the neck of the chamber before the displacement period commences.*
(*c*) Too great a number of displacement cycles, allowing too short a filling period, resulting in the chamber being only partially filled at the beginning of the displacement period.	*Lengthen the time period of the cycle in order that the chamber may fill completely between displacement periods.*
(*d*) Leaky chamber or standing valve, allowing the oil to be forced back into the well when pressure is applied during the expulsion period.	*First remove standing valve and examine for defects; if in order, remove chamber from well to ascertain if joints are leaky.*
(*e*) Curtailing of the expulsion period due to premature closing of the air inlet valve, thus allowing slippage of oil back into the chamber.	*This is easily remedied by prolonging the displacement period.*
(*f*) Trapping of gas in chamber where special chamber valves are used.	*In this case the valve must be properly adjusted.*
(*g*) Clearance loss controlled by the height at which the shoe of the flow tubing is set above the bottom of the chamber.	*This loss cannot be entirely eliminated, but can be reduced to an insignificant amount by setting the shoe of the flow tubing as close as possible to the top of the standing valve, so cutting down the clearance to a minimum as well as assisting in flushing the sand pocket around the standing valve free of any sediment that may have accumulated.*
(*h*) Adherence losses, accounted for by oil adhering to the wall of the chamber, vary with the viscosity of the oil and speed of displacement, and may be from 0.25 to 2.0 cub. in. per sq. ft. of area.	*This is a minor loss which cannot possibly be avoided.*

2. *Tubing efficiency.*—Efficiency of any tubing combination is governed by the selection of the right size of flow tubing and "inductor" string. The relative sizes of these control the volume of air as measured at atmospheric pressure that is required to expel the oil. It is obvious that this volume must be kept at a minimum, as loss of efficiency under this heading can be as high as 50 per cent. of that obtainable under well-regulated conditions.

Bad tubing joints allow the air to leak from the "inductor" annular space into the flow tubing. Losses from this cause are not high as a rule, and should never exceed 1 to 2 per cent. By analysing the casing head gas, using an "Orsat" apparatus, leakage of air into the outer annular space can be detected and the volume leaking ascertained.

Slippage losses can be very high, and are due to the rising oil slug being dispelled at too slow a velocity. Where this is the case, the piston effect of the air or gas is partially lost and oil will fall back into the chamber.

Adherance losses.—Apply to the flow tubing as well as to the chamber. The adherance loss already described will naturally decrease the effective length of the column of oil as it travels upwards towards the surface, therefore, the greater the depth of the well, the longer the initial column of oil must be in order to prevent the ultimate penetration of the oil column by the propulsive element.

3. *High efficiency of the surface equipment* is dependent on good tight joints in all pipework and fittings. The seriousness of air or gas leakage from any cause will be appreciated when it is realised that the leakage of 10 cu. ft. of free air per minute, compressed within the pressure range of 50 to 500 lb. per sq. in. represents a loss of from 45,000 to 112,000 ft. lb. of work. Therefore it is most important that all leaks, such as those emanating from compressor glands, pipeline couplings, valve stems, and other joints should be stopped with as little delay as possible.

Overall efficiency of the displacement pump, starting from the B.H.P. of the prime mover driving the compressors on the one hand, to the work accomplished in lifting the oil on the other hand, can be as high as 35 per cent. for wells 1000 to 2000 ft. deep, allowing 75 per cent. displacement efficiency for the chamber and tubing, and 3 per cent. for line losses. With wells 2000 to 3000 ft. deep, 15–20 per cent. efficiency can be obtained.

In the foregoing pages the author has endeavoured to give a general outline of the possibilities of displacement pumping for raising liquids as applied to the production of petroleum. It is

beyond the scope of this paper to go into details as regards such adaptation to suit the extremely varied conditions of individual oilfields.

There is no doubt that as time progresses, the surface and sub-surface equipment at present available will be simplified and improved upon, as more data regarding what actually takes place during the displacement and ejection periods is accumulated. Eventually, improvements will undoubtedly lead to higher volumetric efficiency of the chamber and modification in the design of tubing employed.

Displacement pumping follows from "straight gas-lift" as a natural sequence for the reason that, not only can the available "gas-lift" equipment be still further utilized, but in addition that control over sub-surface conditions which is possible with efficiently operated "gas-lift" can be continued until such time that the oil-bearing strata no longer yields oil in commercial quantities. The change over to mechanical pumping is eliminated entirely with a consequent saving of very considerable capital expenditure and the production difficulties always attendant on mechanical pumping.

There are fields where the sub-surface conditions are such, that by using carefully designed strings of "flow" tubing, wells can keep producing by natural flow for so long that eventually the application of straight "gas-lift" becomes unnecessary. In a case of this kind, following the cessation of natural flow, it would be advisable to experiment with a displacement pump before deciding upon the installation of mechanically operated pumps and equipment for exploiting the wells in their final stage of production.

Wells are being drilled to increasingly greater depths, and, before long, 6000 to 8000 ft. and deeper will be the rule rather than the exception. The problem of how to produce such wells economically and successfully during their advanced life remains to be solved, and it is very probable that the displacement pump will be the solution.

"Stripper" fields, by which is meant those fields that have reached the final stage of exploitation, can continue to be produced efficiently by displacement pumping in conjunction with "drive" or re-pressuring, as, by such combination the maximum production can be lifted with the optimum formational gas-oil ratio. As the compressor installation serves both for the "drive" and the lifting of the oil, the upkeep and maintenance costs are lower than would be the case with mechanical pumping and "drive" where the "drive" and power units are separate and individual.

"Gas-drive" and re-pressuring cannot be fully effective in depleted fields without the use of the displacement pump.

DISCUSSION.

The President remarked that the paper had been extraordinarily interesting. It seemed to him remarkable that a method of such simplicity as that described had appeared at so late a stage in the development of oil production. It seemed that such an obvious development from the old gas lift ought to be have appeared long before.

The advantage of producing a crude oil free from emulsification seemed to him to be very great; it avoided the necessity and expense of dehydrating either by distillation or by chemical or electrical methods.

The author stated that when using air or stripped gas the absorption of gasoline when blowing up the crude was very small—0.5 of a gallon of gasoline per 1,000 cub. feet. That quantity seemed to him to be remarkably small, even allowing for the fact that the crude was not aerated to any extent. The figure, of course, would depend upon the nature of the crude oil used, but he wished to ask if the author had any comparative figures giving the degree of absorption of gasoline in the air or gas that would have been obtained if the work had been carried out by the ordinary method.

As he knew that Mr. Beeby Thompson had been carrying out some work on similar lines to the author's, he would ask him to open the discussion.

Mr. A. Beeby Thompson said that the system described was specially interesting to him because it was a method which he had frequently employed in Russia something like 30 years ago. At that time air lift work had just been initiated in Russia, and it had been his duty and pleasure to instal the first plant in the Baku fields. After a very considerable amount of success in high fluid level wells, the liquid fell and then troubles commenced. As the fluid level fell in wells, the discharge became intermittent whether they liked it or not, and that was how they had got their first intimation of the usefulness of intermittent working. For a long time it was regarded as most inefficient and most irregular to work intermittently with air or gas, but the productions were extremely satisfactory, and were such as to warrant a continuation. They had been driven to experiment with gas lift or air lift at that time in certain wells, which gave more sand or water than could be bailed or when the casing had collapsed or deflected so much that bailers could not be employed.

At times it became impossible to use bailers of a size which would give a remunerative production of oil. Originally a well might be furnished with a 10-in. or 12-in. dia. string of casing, and they would

use a bailer 2-in. smaller in dia. and perhaps 40 ft. long; but the condition of the well might only permit of a bailer 2 or 3-in. in dia., so that it was impossible to keep the well sufficiently clear of water to obtain any useful production. He recalled that the first well which he had put on air lift was one of that type, where it was impossible to obtain any sustained production, but the first effort they made with air lift resulted in a yield of 50 tons of oil a day. Although a lot of water was present, it formed an emulsion—a very thick emulsion—which fortunately quickly separated in the settling tanks without any trouble, so that they were never worried on that score.

The author had certainly presented many new facts in connection with the displacement system which was coming into more general use. It had been more or less enforced by circumstances in some instances. Producing from very deep wells was becoming an increasingly difficult problem, especially when dealing with "crooked" or partly collapsed wells and those presenting troubles with water and the formation of emulsious; so that some producers were really being compelled to investigate such systems.

It had surprised him very much to find that the author was able to get such high efficiencies as those recorded, but he took it that these were largely due to the fact that he was dealing with wells of only 1000 to 2000 ft. depth. The oil producer to-day, who had to deal with depths of a mile or more, was faced with far more complex problems. Experience had proved that such wells could be operated, but he felt sure that much more trouble would be experienced in dealing with those deep wells than in producing from the shallow wells.

Regarding the displacement system generally it was constantly alleged that it was a too inefficient process for general use, but it was necessary to be careful how we applied the term "efficient." That word was often used very loosely, and did not always convey a correct picture of the duty with a disclosure of all facts. In the case of Russia it might be said that the air lift was very inefficient mechanically; one large compressor being needed very often to work a single well; but if by ordinary bailing methods they got no oil from a well at all, and they had recovered 50 to 100 tons a day by means of air lift, the result could not be described as inefficient. It was very much the same with the displacement system described by the author. There were occasions when "mechanical efficiency" did not enter the picture, for surely it mattered very little, other things being equal, what the "mechanical efficiency" was if a well produced a greater profit than with another type of plant of greater mechanical efficiency. There were occasions when the gas straight lift and the displacement system could be used with gas

supplied direct by high-pressure wells, as was actually being done in some fields, where it was only necessary to lead the gas to the well and operate without any compressors at all. It mattered very little what the "efficiency" was in a case of that sort; but even when compressors were employed, if the pressures were not too high, and the air volume was properly controlled, production costs could often be cut down. When working very deep wells there must be a greater fall in mechanical efficiency owing to the loss of gas in the annular space between the two tubes, and in that direction there remained much experimental work to be done. The chamber valve effects a great economy in the gas but introduces complications and troubles. He could visualise that in the future, if the process described by the author advanced in the way he expected, special flush-jointed tubing would be used, thereby reducing the annular space to a minimum, and avoiding all the heavy frictional losses which resulted from collars and from joints not properly meeting. At present the eddying effect at each joint in a well a mile or more deep must be very great.

He had felt very serious misgiving in the earlier stages of the new development concerning paraffination. Naturally, if one could raise oil without diffusion or atomization of the fluid, one would not expect a great deal of paraffination; but he was perfectly astounded to see, only a few weeks ago in Rumania, wells being operated with the displacement system in what was probably one of the worst fields in the world for paraffination (Ceptura), and producing steadily and continuously for long periods. Months had elapsed in some cases without the wells receiving attention, and these were wells where they had found no means, so far, of producing except by pulling the tubing every second day, or else admitting live steam and melting the whole of the paraffin in the tubing. There was, therefore, very definite proof that the system was applicable to one very difficult condition which had defied all other methods of attack.

The author had not dealt with a type of well which was one with which he (the speaker) often had to consider—namely, a well which started off with a fairly high fluid level that gradually fell until it was practically a dry pumper. Wells of this type were expensive to pump as it was usually found that intermittent pumping led to loss of production. Personally he was satisfied that it would be found possible to produce from that type of well after a little more experimenting with displacement lift. He had been exceedingly surprised to note the statement made by the author, evidently with due consideration, that a larger production could be obtained from a well by the process described than by pumping. Every production engineer knew that pumps operated very erratically

under some working conditions, but it was difficult to understand why all wells gave a higher production under the system described than by pumping. Perhaps that statement needed some qualification, or some explanation of local production troubles.

The system was especially applicable to crooked wells and wells of small yields where pumping troubles enforced the constant employment of pulling gangs. The author again went much further than he would dare to go in saying that wells could be worked by that process until complete exhaustion.

There was one point which he did not think the author had adequately stressed in his paper, and which was very important—that the process gave a means of producing properties automatically, either by individual control or from a central station. He had visited a property in California, only a year previously, where a whole plot was being worked entirely automatically, without any men on the lease, except for measuring or observation; and even now, in Rumania and in other places, large groups of wells were being worked automatically, with only a man running about to see what was happening.

The capital cost of an installation was not excessive for a group of small producers. The tubing was one of the main costs, for only very good tubing should be employed for that sort of work, where, as the author explained, very violent shocks were thrown on the tubing and fittings at certain periods of the cycle of operations.

He certainly had great belief in the process and in its future, and although, as he had remarked, so many attacked it from the point of view of "efficiency," he thought that that was one of the factors that should be subordinated to other and more important considerations, because pumping deep, and often crooked, wells, giving generally a certain amount of water, was a most expensive and difficult business. As the cost of labour rose on the various fields, the pulling costs increased, and there was always the very serious danger of dropping the tubing or rods during the frequent pulling operations at deep wells.

Mr. B. J. Ellis congratulated the author on his enthusiasm for the new form of pumping, and on having dispelled some of the mystery with which makers of displacement pumping equipment had attempted to surround their system. Members had learned from the paper that a displacement pump was merely a chamber made of casing or tubing fitted with a standing valve and two strings of tubing, and that all that was needed was a supply of compressed air, an automatic valve with a delay action of some sort, means for measuring and recording gas and oil quantities and pressures, and

someone with patience and ability to analyse the results and juggle with the sizes, pressures and quantities until the best results were obtained.

There was apparently little more in displacement pumping than in rod pumping—probably no more if equal efficiency was accepted for each system—so that the mystery with which manufacturers sought to surround displacement pumping and their anxiety that good results should be obtained right away might be because displacement pumping, unless more efficiently run that rod pumping, was more expensive in first cost and operation.

Unfortunately, the author had given no ideas of cost of compressor plant, gas lines, etc., for displacement pumping, or of the operating costs. These, of course, were of the utmost importance, and he would suggest that the implied assumption was not tenable, that because compressors had been used for gas lift and were available their cost need not be taken into account in considering the relative merits of displacement and other pumping methods. He did not know whether the author had any figures available ; if he had, he for one would be very glad to hear them. In case the author had none, he had collected some information on which he would be glad to have the author's comment. The cost of plant for rod pumping in a foreign field was of the following order : Pumping powers, including tractor winches, £100 to £300 per well ; cable tool pumping rigs, £350 to £500 per well ; individual pumping units, including tractor winches where necessary, £200 to £1,200 per well. Power consumption per barrel was : pumping powers, ¾ to 3 B.H.P. hours/barrel ; cable tool pumping wells, 2 to 4½ B.H.P. hours/barrel ; individual units, 1¼ to 3½ B.H.P. hours/barrel.

On the assumption that from 1,000 to 2,000 cu. ft. of free gas compressed to 300/500 lb. per sq. in. was necessary to raise one barrel of fluid by displacement pumping, he estimated that the erected cost of plant in the form of 500,000 cu. ft. gas engine driven compressors with an allowance for pipe lines, extra tubing, etc., would be between £300 and £500 per well, and the power consumption between 4 and 8 B.H.P. hours per barrel of fluid raised.

From these figures it would seem that capital costs for displacement pumping equipment were about the same as for cable tool pumping rigs, and that the power consumption was about double. Both capital cost and power consumption were considerably higher than for pumping powers, and he was led to the conclusion, therefore, that displacement pumping was more likely to show to advantage on producers of considerably larger capacity than 10 barrels per day. Even on wells of 100 barrels per day, such as would require an individual pumping unit or cable tool pumping rig, the extra cost of power had to balance the reduced cost of pulling

and it would seem that only when operating at the peak of efficiency could displacement pumping compete with more ordinary methods unless some other feature, such as very crooked holes, weighed on its side. Even so, it must be remembered that considerably greater efficiency than that indicated by the figures just mentioned was possible with rod pumping by using mechanically efficient units, and by slowing down the motion and seeing that a high volumetric efficiency was obtained. One record which he had showed that with a unit costing installed about £500, a production of 60 barrels a day was obtained from a well with pump set at 2,200 ft. at a power consumption of less than one B.H.P. hour per barrel. The unit pumped at 5 strokes a minute, and the amount of attention required was very small.

With regard to the control of production by the adjustment of fluid levels and back pressures, it seemed to him that the problem was exactly the same with both displacement and ordinary pumping. If oil levels and gas pressures were such that gas locking occurred in an ordinary pump, they would have the effect of reducing the efficiency of a displacement pump by partially filling the chamber with gas. Adjustments to the oil levels, gas pressures and pump levels could be made to prevent gas locking, and he imagined exactly similar adjustments would be needed if proper efficiency was to be obtained from a displacement pump.

However, in spite of its limitations, he felt sure that displacement pumping would eventually prove, for certain conditions, to be the most economical method of production, and he wished to thank the author for putting forward so clearly its many merits and for giving so much valuable information.

Dr. A. Wade said that the paper illustrated to some extent the great advance which had been made in the technique of oil production since the war. He personally had had some experience of gas lift, and he thought he could answer the question which the President had put as to why it was that a comparatively simple arrangement like displacement pumping should only have been developed within the last few years, or at any rate brought to its present pitch of perfection. In 1921–1922 he had happened to be working in Texas on shallow fields in which they had a good deal of gas at high pressures, and a good many wells for which it was desirable to reduce the pumping costs as much as possible, but in trying to instal gas-lift systems the conservative driller and operator were absolutely antagonistic; they fought every effort to bring in new ideas or to try new methods with the greatest bitterness. The idea of putting any back pressure on the sand was absolutely abhorrent to them; it caused hot discussions, and new ideas did not go ahead very quickly, especially when one was dealing with independent

operators and the smaller companies. In the particular case he had in mind, they did manage to get some work done by gas lift, utilising gas from their own gas wells with fairly good results.

It seemed to him that the advantages of the displacement system did not depend entirely upon comparative costs as compared with ordinary cable tool pumping and gang pumping, so that with regard to the shallow types of wells—he could not speak with any experience of the deeper types of wells—he did not think the question of cost was what mattered most. What mattered most was all the other advantages which were so well described in the paper; for instance, the avoiding of emulsions, the avoiding of paraffining up of the tubes, and so on. So far as costs were concerned, he thought that with regard to a shallow field, properly operated, with a number of wells on the same power, the costs might run out a good deal cheaper than the author stated in his paper. The author gave a figure of 10 cents to 40 cents a barrel, but he knew of cases in shallow fields which were being operated at even lower costs than that. But with regard to displacement pumping he did not think that that would be the main point. The main point was general efficiency, not just efficiency as applied to initial costs or costs of pumping, but general efficiency —the amount of oil produced, the life of the well, and the avoidance of troubles. Those were the questions which might make displacement pumping of very great importance.

Since it was, in his opinion, impossible for any one man to have practical knowledge of all the various conditions under which oil is produced, he thought that one was inclined to have in mind those conditions with which one was most familiar in considering new methods and departures from the orthodox. This made it necessary to weigh carefully criticism and one's own judgment. He thought that, while it was quite certain that displacement pumping would not supersede older methods in conditions which were favourable to such methods, he was equally certain, judging by comparatively recent experience of his own, that there were fields in which displacement pumping might be adopted with advantage and profit.

He had intended to ask a question which he thought Mr. Beeby Thompson had partially answered. The author stated in the paper that by means of displacement pumping the paraffining up of the tubes was to a great extent avoided; but what he would like to know was what was the effect upon the paraffin content of the sands in the producing section of the well. In certain wells with which he had been connected some years previously, a good deal of trouble had arisen with regard to the paraffining up of the wells at the point of production in the sands, and he would like to know how displacement pumping affected that. He thought Mr. Beeby

Thompson had very largely answered that question, because he seemed to indicate that that type of pumping obviated the difficulty to a very great extent.

Mr. T. A. Smith said he had listened with interest to the paper, but found it impossible to agree with the author on the matter of efficiency when using compressed gas. The author claimed that 35 per cent. was easily obtained. That meant that he was beating by at least two or three times "bogey" for the course where "bogey" was the theoretical efficiency.

In Table III. the author gave quite a lot of data, but the table was incomplete, inasmuch as the efficiencies were left out. He had calculated a number of them—they varied from 2·88 per cent. to 15 per cent. Unfortunately the best efficiencies lay to the left of the thick line, where advantage could not be taken of them owing to difficulties with the "slug" flow.

There was only one way to obtain an apparent efficiency of 35 per cent., and that was to blow gas down a well that did not actually need it, and take credit for the work done by the formation gas liberated with the oil. This was the practice of companies selling compressors. He had in his hand the handbook of a large compressor selling company, which gave the efficiencies of gas lift for ten wells ranging from 6·5 to 21·4 per cent. In actual fact the efficiency was from 3 to 11 per cent., and it was quite obvious that most of the ten wells could have been made to produce themselves. A producing well was a machine, and most engineers could make machines work up to 5 or 10 per cent. efficiency.

It appeared to him to be as unreasonable to place a small pump, pumping water into the Thames at Westminster Bridge, and to claim credit for all the water passing London Bridge as to claim 35 per cent. efficiency for gas lift.

Another feature of gas lift was the volume of gas it was necessary to use. In Table III. this ranged from 1200 cu. ft. to 410 cu. ft. per barrel. All that gas had to be put through gasoline recovery plant, and the cost of treating it should be charged up against the cost of lifting the oil. Unfortunately the usual practice was to credit the gasoline plant with the gasoline produced, thereby giving a very distorted view of the gas-lifting operation.

He would like to know what actual "flexibility" could be obtained with gas lift that could not be obtained with other pumping equipment, also what possible scientific explanation there could be of a well being supposed to give more oil on gas lift than on any other properly controlled pumping system.

When the total cost, inefficieney and cost of maintenance in working order of a gas-lift system was considered, it must be many

times more costly than any other equipment. No engineer used compressed air on the surface if he could possibly transmit power in any other way.

He did not like to be destructive without being constructive, and he submitted that the most reasonable way of transmitting power about a small oilfield was to use the oil itself as a hydraulic medium. The lines carrying the oil to the central station would not have to be duplicated. It was unnecessary to use "sucker-rods" down a well. With a reasonable hydraulic system the pump-stroke could be almost anything that one wished, and such pumps could not gas lock. The pressures might be very heavy at the bottom of a well using a hydraulic system, but he did not think they would be any worse than the shocks of the displacement system.

The use of compressed gas, as far as efficiency was concerned, was based on a fallacy, supported by false argument, and its economy was a myth.

Dr. J. A. L. Henderson said he had listened to the paper with great interest, because it dealt with a new phase of oil production, being a particular adaptation of the gas lift which they had been long looking for. Personally he had sought for information as to some proved practical method of producing oil in that manner, but could only obtain it from catalogues of companies selling their own apparatus. It was very well worth while, therefore, for the Institution to have a paper on the subject from Mr. Millar, who had presumably investigated the subject thoroughly; but he thought that the paper should be treated as an introduction to the subject of displacement lifting, because so far as his inquiries had gone there remained many questions to be solved in relation to its successful application under varying conditions in the different fields, and it was still in the earlier experimental stage. References to literature on the subject would make the paper more complete. Amplification of the paper by furnishing figures of the cost of the installations in relation to both deep and shallow fields, where gas could be used, and where air had to be applied, would add to its value. The advantage of this method of production was undoubted in dealing with deep, crooked wells, particularly where the production was relatively small. Could the author indicate what was the relation of the profitability to the yield per well when operating such a system, as compared with other methods of oil lifting in the various fields he had visisted in connection with his investigations, and what were the smallest yields which had been profitably worked? Investigations had indicated that, on certain fields, the relative cost of installation and operation of the displacement pumping system would be greatly above that of the ordinary pumping systems.

Mr. L. Owen said that most of the points where he was in agreement with the author had been reviewed by previous speakers, and the late hour forced him to deal only points where he disagreed.

He wished that the author had shown a little less of what might be called "dogmatic enthusiasm" for displacement pumping as compared with other tested methods of oil raising. The paper was full of unqualified optimism, some of which was not likely to be borne out in practice.

A most important factor, which was almost disregarded in the paper, was that of capital cost. In a field where "straight" air lift had been tried and had not come up to expectation, he could understand the advantages of utilising the existing plant for some such alternate method as that brought forward, but it was quite another thing to suggest the scrapping of an efficiently run mechanical pumping plant and to burden a field with the large capital cost of compressor stations, gas-lines, etc., and the incidental heavy running costs. Such a policy could be financially sound only in very exceptional cases.

This brought the speaker to the question of cost of raising oil—a figure which depended very largely on the method and idiosyncracies of the accounting department. He would like to know how the author's figures were calculated. If a reasonable amount were allowed for plant depreciation, even on a second-hand basis, one could not, in his submission, raise oil for anything like 3 cents a barrel, unless circumstances were very favourable indeed.

Mr. Beeby Thompson had already raised the point as to pumps becoming gas-bound. Might the speaker suggest that the author, in making the statement referred to, had in mind only short-stroke and not long-stroke pumps ?

He agreed with Mr. Smith's remarks as to the values claimed for overall efficiency. The figure of 35 per cent. was astounding, and he had thought that it was a misprint for 3·5. Perhaps that was the explanation ?

Mr. Charles Dabell said that he liked the principle set forth in the paper. He liked it because it was something new; it was a distinct step forward. They had jogged along for many years with jerker outfits, and then had progressed towards the compressor stage, which had a very good run, and also was certainly a step forward, and he did feel that the system was something which should receive all the encouragement it could from the Institution.

Mr. Owen had raised the question of cost, which had come into his own mind. From a glance at the kick-off arrangement, he supposed it would cost £50 or £60 per well, and at the present price

of crude he thought that in many producing fields manual labour at 1s. 6d. or 2s. per day would be more economical. Much, however, depended upon the timing of the producing periods.

Mr. C. A. Andrews, in reply, thanked members for the very instructive discussion. Any remarks that he made in reply must, of course, be taken to be purely the expression of his own opinion, and not in any way committing Mr. Millar.

With regard to costs, after all, the initial costs were not so important as the return obtained on that cost, and it certainly had been the experience that the return on the costs amply paid for, in some cases, abandoning the jerk lines and putting the wells on to the displacement-pump method of production.

Mr. Beeby Thompson had mentioned the paraffining in Rumania. The reader's experience had been similar with regard to the paraffining in the "riser tube." As regards the cost of labour, mentioned by another member, he was afraid the figure of 1s. 6d. a day was hardly right; it amounted to more than a dollar a day per man, and there were three shifts. So far as native labour was concerned, it was extremely unreliable, whereas the displacement-pump system was largely automatic, and at worst required but few men, being in any case much more reliable than native labour.

On the motion of the President, a vote of thanks to the author and to the reader of the paper was carried with acclamation.

The following written contributions to the discussion were received subsequently :—

From **Mr. Robert Stirling :** He had experimented during many years in the application of compressed air to raising oil from wells, chiefly by the air-lift method, and gave the results of his experience in his "Gas Air-lift Pocket Book." Mr. Millar has gone very fully into the application of the displacement method to oil wells, and he agrees with him that it is the natural sequence for pumping when the level of the liquid in the well falls too low to admit of economical pumping by the air lift. The "intermittent gas lift" referred to is too uneconomical to be considered, and has no good quality to recommend it.

Although the efficiency of the displacement pump will compare favourably with that of the "beam pump" in many wells, he cannot agree with Mr. Millar's statement that the mechanical efficiency of the displacement method in a 2000 ft. well can be anything like 30 per cent., even theoretically. His reasons for this are that the apparatus indicated by Mr. Millar is almost identical with that proposed in the British patent No. 22765/1901 (U.S.A. No. 717048/1902) and tested in wells in Baku. Of the

many designs of displacement pumps proposed and tried in oil wells this is, so far, the best and most promising. The chief points to be observed in designing the apparatus, as detailed by Mr. Millar, are those set out in the specification of the patent. No doubt the surface fittings for controlling the air supply have been much improved, but the essentials are apparently similar.

The time required for each discharge cycle, and the velocity of the "slug" of liquid in the flow tube, depend entirely on the rate of air supply. If the velocity be low, the result will be, as Mr. Millar points out, that an excessive proportion of the liquid will fall back, and a portion of that which reaches the chamber may not be ejected by the rush of the expanding air, when the weight of the "slug" of liquid has been discharged. On the other hand, friction losses increase with the velocity.

The efficiency of the air-lift in a 2000 ft. well is little over 30 per cent. with 40 per cent. "dip" under favourable circumstances, and this falls to little over 10 per cent. with 10 per cent. "dip." He would not expect a much higher efficiency in practice from a well proportioned displacement pump, seeing that the theoretical efficiency of a cycle is only about 20 per cent. With the displacement pump each cycle is complete, and the intervals between the cycles may be timed to meet the yield of the well, without loss of efficiency, the only difficulty being to arrange for an intermittent air supply. With the air-lift the apparatus must be proportioned so that the yield of the well provides a steady flow, or there must be serious loss of efficiency.

References in the paper to "back pressure on the oil sands" shows the usual "confused thinking," which is quite excusable in view of the amount of nonsense found in the literature on the subject. The fact should be clearly realised that the pressure on the oil sand depends solely on the weight of the liquid column in the well, and can be altered only by lowering the height of the column, by regulating the quantity of liquid pumped in relation to the yield of the oil sand. When using the air-lift the air pressure gauge indicates exactly the weight of the column of liquid in the well, and if the height of the column is measured the average specific gravity can be ascertained.

The "Gas Air-lift Pocket Book" deals in detail with these matters, and shows how little mystery there is in the use of compressed air for pumping oil wells, and how simple is the proper application of the air-lift method, and the promising outlook for the displacement method, when the air-lift stage of the well has passed.

From **Mr. W. J. Wigney**: Mr. Millar's paper deals generally with displacement pumping on groups of shallow, small-producing wells operated by a compressed air or gas system in which a constant

pressure is held on the input gas or air lines. It is to be presumed that this constant pressure is held by regulating the pressure of the intake line to the compressors. If the group of displacement pump wells is not regulated in a positive manner so that they would go on their injection periods in sequence, the fluctuating demand for input gas may cause difficulties with the pressure regulation. This would be particularly true with deeper or larger producing wells.

For displacement pumping it is not essential to hold the input gas or air lines at a constant pressure, and, in fact, it may be often preferable not to do so. At deeper and larger producing wells in particular, consideration should be given to the supplying of input gas or air directly to each well in turn at exact intervals of time. In this case each well would automatically build up its own maximum lifting pressure in accordance with well conditions and rate of input gas or air delivery.

Mr. Millar's figures for gas or air consumption in relation to lifting pressures are based on the condition that input gas or air is closed off from the well at the moment the oil slug reaches the surface. Smaller volumes of gas or air than those quoted would be used if a check valve should be installed in the middle string of tubing on a level with the top of the chamber. With this check valve in place input gas could be closed off from the well, and the exhaust line opened before the slug had reached the surface in such a manner that the oil would be brought up the remaining distance by making the utmost use of the gas expansion taking place between the check valve and the oil slug.

With regard to Mr. Millar's points in favour of displacement pumps as against plunger pumps, I would suggest that the efficiency of the displacement pump does not decrease in nearly the same proportion for increase in depth as the plunger pumps, owing to the infrequency of its action and almost total absence of moving parts.

There is the further fact that below a certain depth plunger pumps are not a practical proposition, especially if operated in a crooked hole.

In producing a given size of displacement pump installation up to its maximum for any particular chamber level, consideration should also be given to the time factor. In order to complete the number of cycles required for maximum production the injection period must be short enough to allow the chamber to fill before the next cycle commences. On deeper and larger producing wells this factor has considerable importance.

From **Mr. C. Dalley**: The majority of those who read Mr. Millar's paper will no doubt sub-consciously apply the particulars to some field or fields with which they are acquainted and

endeavour to make comparisons and criticisms. Not only are the differences between various oilfields great, but many oilfields in themselves vary to such an extent that no one method of production is practicable.

The paper should be read rather in the light that displacement pumping should or may play an important and profitable part in the future producing life of any oilfield.

In a great many oilfields, up to a comparatively recent date, when the wells ceased to flow there was no intermediate step between flowing and ordinary pumping. As a result those fields ultimately settled down to a pumping proposition. There is, however, a stage in the life of almost every oilfield where the artificial utilisation of gas becomes a profitable addition and fully justifies its inclusion, even where it is necessary to provide compressor plant. It certainly is when high pressure gas is available, as is frequently the case, from some other part of the field. In an oilfield, therefore, which originated with flowing wells which subsequently become pumpers, intermediate stages of production are now introduced, available surplus gas being used for repressuring, gas drive, straight gas lift, in addition to displacement pumps operated by gas. In those cases where electricity is generated from units which use gas as fuel, the utilisation of electricity is also indirectly the application of gas.

It is quite erroneous to stress the particular efficiency and cost of any one of these operations individually. Actual information of importance is the overall efficiency, flexibility and cost of the production of crude oil in a given time utilising all or any of these methods.

Mr. Millar has given actual figures to show that displacement pumps were profitably employed instead of straight gas lift in dealing with emulsified crude. In such a case it is not an argument for the field chemist to say, "Produce emulsified crude as cheaply as possible and we will break down the emulsion," nor for the field engineer to endeavour to produce oil free from emulsion at all costs.

On the same field referred to by Mr. Millar, displacement pumps were installed on six wells previously operated by an underpull power. The substitution resulted in a definite saving of £400 per annum. Whilst these provide interesting and definite examples, they must only be considered as a part of the whole scheme of efficiency.

In cases where increased outputs are recorded in comparing various methods of production, it should be emphasised that the comparison is made for a given time and not ultimate production.

If Mr. Millar's paper is read under the conditions and qualifications above mentioned, it will, I think, be clear that displacement pumping has, in certain definite cases, provided such an economic supplement to other production methods as to reduce production charges to the minimum. The progress made in these cases indicates that the use of displacement pumps is capable of extension to other old and new fields. For this reason alone the information provided in Mr. Millar's paper makes a valuable addition to the proceedings of the Institution.

Mr. Albert Millar, in reply, wrote: Beyond manufacturers' catalogues and a brief article by Raymond F. Carr in the second edition of "Petroleum Engineering Handbook," the author is not aware that any literature has been published on the subject of displacement pumping systems.

Having made a special study of air and gas lift and production methods in general for some years past, it is only natural the writer should have followed closely the development of displacement pumping from its initiation to the oil industry. Through the kindness of friends, he has been able to keep in close contact with the results of experimentation and developments under varying conditions on other fields. Such information has been most valuable to the author, especially where it applied to the exploitation of deeper wells.

As mentioned towards the end of the paper, the problem of producing deep wells more economically and successfully still awaits solution. It is the author's opinion, based on results already achieved, that within a comparatively short time the displacement method will be extensively adopted for lifting oil from such wells after the flowing and "gas-lift" stages have passed. In all probability, certain modifications will be necessary to adapt the method to suit special conditions.

Replying to the President's remark as to the delay in the development of displacement pumping, there is little doubt this method would have been more generally adopted and greater strides made towards mechanical perfection had it not been for the fact, as Dr. Wade had rightly stated, it has, in common with several other innovations to the petroleum industry, met with considerable opposition on the part of many field men and operators who, without rhyme or reason, are antagonistic to the introduction of new methods. In the majority of cases, such innovations are beyond their comprehension, and must therefore be kept off the lease at any price.

Regarding the low percentage of gasoline extracted by the lifting medium, whether air or gas, the figure of 0·5 gal. per 1000 cu. ft. mentioned in the paper proves to be a very liberal one in practice.

Actual experience shows that practically no intermingling of the oil and lifting medium takes place in wells being produced by the displacement-pump method, provided the most suitable pressure and properly designed chambers and tubing strings are used. These will ensure the column of oil to be lifted at each cycle to be of the right length, and the velocity such that minimum slippage or penetration occurs. Only that portion of the air or gas which actually comes into contact with the crude will absorb gasoline from it, and only traces of gasoline will be found in the air or gas following right on the tail of the slug of oil lifted. In the majority of cases the remainder of the air or gas exhausted will show but a negligible percentage of gasoline.

After the oil enters the chamber, it is at almost atmospheric pressure; consequently it contains only a small quantity of gas in solution. The moment the ejection period commences, the oil becomes subjected to considerable pressure. Under such conditions, it is not so easily stripped of even a portion of its lighter ends, and this is further assisted by the fact that air or gas under pressure will not absorb so readily.

The percentage of gasoline by which the lifting medium becomes enriched depends on conditions of flow, pressure, velocity and gasoline content of the crude lifted. With crudes containing from 10-15 per cent. gasoline, the percentage of enrichment would be infinitesimal under good working conditions, and the figure given, i.e., 0·5 per cent., can be reasonably anticipated. Standard charcoal tests of the lifting medium show this figure to be obtainable without difficulty.

Tests of oil samples taken from wells being produced by pumping and "gas lift" and tests made of samples taken after the installation of displacement pumps show a decided increase in gasoline content of the crude when the wells are produced by the latter method. The reason for this is two-fold:—

1. The use of the displacement pump will allow the gas being produced from the formation to be very considerably reduced. Under certain conditions it can be cut as much as 50-60 per cent. As is well known, gas produced from the sand or out of solution will enrich itself at the expense of the oil. It follows that the less gas produced per unit volume of oil, the smaller the quantity of gasoline likely to be stripped from the crude.

2. Many wells being produced by an ordinary plunger pump have to be exploited without back pressure; this usually tends to a higher gas-oil ratio and loss of gasoline content. With straight "gas-lift" wells, more especially the deeper ones, difficulty is often experienced in controlling the character of the flow, with the result

that excessive aeration takes place. This is due to the air or gas expanding to ten to twenty times or more its original volume during its passage up the "flow" tubing.

In reply to Mr. Beeby Thompson, the author would like to point out that the statement regarding efficiencies as high as 30-35 per cent. and 15-20 per cent. being attainable is quite correct under most favourable conditions. The writer does, however, realize that he should have amplified the statement, which might otherwise be misleading, by explaining they referred to an example :—

(a) Where upper-chamber valves are used, thus conserving the gas in the annular space which would otherwise be exhausted at each cycle.

(b) That the volumetric efficiency of the chamber is 75 per cent. on an average.

(c) That the length of the slug and velocity of flow is such that "slippage" is minimum.

(d) That the supply of gas is cut off as early as possible in order to take maximum advantage of the expansion of the lifting medium.

(e) That the compressor station is located in a central position, which shortens the total length of the supply mains and so minimises leakage ; moreover, that the compressors receive the gas at 35-50 lb. or more pressure at their intake, either from an absorbtion plant or from separators.

For instance : With a 2-in. in 3-in. tubing combination 1000 ft. in length. A chamber having a capacity of 7·5 cu. ft. and exhausting all the gas each cycle, 512 cu. ft. of gas referred to atmospheric pressure will be necessary for each cycle. By using an upper chamber valve, only 325 cu. ft. would be required.

From actual practise it has been observed that 150 lb. per sq. in. effective working pressure in the chamber will give good flowing efficiencies. To this figure, however, 20 lb. per sq. in. must be added for line and tubing annular space friction losses. This additional pressure of 20 lb. will allow full advantage to be taken of the initial impact pressure effect referred to in the paper. With efficient compressors, approximately 37 H.P. will be required to compress 325 cu. ft. of gas per minute referred to atmos. pressure, from 40-170 lb. gauge. The quantity of oil lifted will be 5·6 cu. ft. If this oil has a sp. gr. of 0·880, the weight will be 307·5 lb. As it will be raised 1000 ft. in 50-55 seconds, or at an average velocity of 18-20 ft. per second, this is equivalent to 350,000 to 360,000 ft. lb. of work. The overall efficiency will be 28 per cent.

Should the gas pressure at the compressor intakes be at 50-lb. gauge, an efficiency of 35 per cent. will be attainable under similar conditions. With the gas at atmospheric pressure at the compressor intakes, the efficiency would be 12 per cent.

In order to obtain the most effective pressure in the chamber with a 2-in. tubing combination over 2000 ft. in length, a slightly higher discharge pressure will be required at the compressors. By this means fullest advantage can be taken of an early cut-off and the expansion of the lifting medium.

Experiments in connection with "riser" tubing are in course of progress; it is anticipated that friction losses in the annular space can be lessened and that the area of that space can be reduced.

Actually, the losses per 1000 ft. of 2-in. line are comparatively small. For example, 350 cu. ft. of air per minute referred to atmos. pres. at 170 lbs. per sq. in. will have a pressure drop of approximately 7 lbs. per 1000 ft., and approximately 25 lbs. per 1000 ft. of annular space. It is estimated this figure can be cut down to 10–15 lbs. per sq. in. by using flush joint pipe.

Where an upper chamber valve is used and the spring is well adjusted, full advantage can be taken of the "initial impact," and the annular space friction losses will not play such an important role. Neither will it be so essential to keep the annular space to the minimum, as the upper chamber valve conserves the air or gas in that space; moreover, 2-in. in 3½-in. tubing can be used, and instead of the gas having to be compressed to 170 lbs. per sq. in. 160–165 lbs. would be quite sufficient.

Although it is most essential that engineers should at all times strive to obtain the highest possible mechanical efficiency, the author agrees with Mr. Beeby Thompson and Dr. Wade that the mechanical efficiency is not the only factor that has to be given consideration when judging the merits of a system.

Production engineers especially are called upon to take a very comprehensive view. To lift the maximum quantity of oil from wells varying from 1000–6000 ft. deep as cheaply as possible, is but one of the items that has to be studied; there are others equally as important, for instance :—

(*a*) To lift the oil in such a manner that it is not depleted of its most valuable lighter ends to any extent.

(*b*) If water is present, it is most essential that it be lifted with the least possible emulsification.

(*c*) Should sand be troublesome, the oil must be raised with minimum amount of wear and tear to equipment. The production of an excessive amount of sand may cause complications as time goes on, due to altered sub-surface conditions. It is very necessary

that the minimum percentage of sand be produced per unit volume of oil, and whatever that percentage may be, it must be under strict control.

(*d*) Precipitation of paraffin in the tubing, as well as paraffination of the producing sand may present another problem. We are all aware that as a field gets older and the gas pressure much reduced, the oil will become more viscous owing to the crude containing less gas in solution. This is the period when clogging of the sand pores with paraffin takes place. In order to counteract this clogging as much as possible it is advisable to reduce the amount of gas being produced and to maintain back pressure on the producing sand.

(*e*) Water encroachment has always been a serious matter Checking and holding water encroachment under control means minimising the danger. With certain types of structure advantage can be taken of such encroachment, which, if well controlled, can be used as a means to insure almost complete recovery of oil from the sand.

(*f*) Where gas drive is in progress with a view to obtaining maximum recovery, complete control of the " drive " is of paramount importance if the " drive " is to be successful.

(*g*) Another very important point is the conservation of the natural gas energy in the producing sand, as this has a direct bearing on the ultimate production recovered. It is the duty of every production engineer to do his best in this respect.

It often happens that the production engineer is faced with several, if not all these problems at one time ; they are of equal importance and have to be given individual consideration if the structure or field is to be exploited in a rational manner. Preference should therefore be given to that system of producing which will insure the engineer the best all-round efficiency and control over sub-surface conditions, even though only moderate mechanical efficiency may be obtainable.

With reference to the type of well referred to by Mr. Beeby Thompson, which started off with a fairly high fluid level that gradually fell until it was practically a pumper and then became both difficult and expensive to produce, this has been touched upon under " small producers."

The writer believes that such wells can be economically produced by means of the displacement pump. A study of the well's characteristics will reveal the maximum height to which the fluid level will rise in a given time. When this is known, a properly proportioned chamber and tubing to suit the conditions of the " lift " can be chosen and the cycle shortened or lengthened to suit the rate of inflow. It is just as simple a matter to arrange that the

fluid be displaced once every thirty minutes as once every three hours or longer, and there is not the slightest necessity to speed up the cycles above the number required to obtain the optimum production.

Dealing with "potential" production, reference to the paper will show that the writer mentioned "in nearly every case." He does not wish to infer that an increase can be anticipated in all cases.

In comparatively shallow wells producing a good quality crude (by this is meant an oil which is not heavy and viscous or extremely light and containing a high percentage of gasoline) which are not subject to sand or water troubles, the ordinary plunger pump can be made to lift the maximum volume obtainable, but how often is it the good fortune of the production engineer to deal with such ideal conditions?

As wells get deeper, or, as Mr. Beeby Thompson states—"about a mile deep or even more," mechanical pumping becomes an increasingly difficult operation. After passing 4000 ft. difficulties are encountered which seldom arise at shallower depths, and the volumetric efficiency of the plunger pump falls very considerably with increase of depth.

The volumetric efficiency will be high when a plunger pump is first lowered into a moderately deep well, but it falls steadily as time goes on, due to wear and tear of the plunger, barrel, ball and seats. In some cases the well has to be pulled frequently to change worn parts.

It has been found that a displacement pump will still be in good mechanical order after six months and more running under moderate conditions, and assuming the well is still making oil at the same rate as when the pump was installed, there will be no change in volumetric efficiency.

Actual experience has shown a displacement pump to be in perfect order after a year's work under good conditions. This should be compared with the working of a plunger pump which requires pulling periodically for repair. Then there are the stoppages caused by sucker rod defects, etc., all of which entail loss of production, apart from the loss of volumetric efficiency previously mentioned. Mr. Wigney is quite correct in stating that plunger pumps below a certain depth are not a practical proposition, especially if the hole is crooked.

It is where conditions are less favourable that the displacement pump shows to best advantage; because depth, water, emulsion, sand, paraffin, crooked holes, gas interference, etc., have little or no detrimental effect on the volumetric efficiency of the displacement

pump. An outstanding feature is that the maximum quantity of oil can be lifted without sacrificing that control over the flow conditions from the sand to the well which is so very essential.

In stating that a well could be exploited by the displacement pumping method until complete exhaustion, the author does not wish it to be understood that he meant until 100 per cent. of oil had been recovered from the sand. What he wished to imply was that the displacement pump will lift the oil as long as it will flow into the well from the sand. The minimum quantity that can be economically lifted depends on depth of well and fluid level, just as is the case with the plunger pump.

The author cannot agree with Mr. Ellis that juggling with sizes, pressures and quantities would result in " the best results being obtained." As soon as the characteristics of a well are known, it is possible to design a chamber with the right tubing combination and working pressure that will ensure most efficient results. A certain amount of experimental work has to be done on individual wells in order to ascertain the exact amount of back-pressure required to cut down the gas-oil ratio and hold water encroachment in check.

In the paper the author stated his intention to deal with the more advanced life of producing wells, particularly after wells had passed the flowing and normal gas-lift stages, and it will be observed that he has assumed that plant, such as compressors, pipelines, etc., would continue to be available.

Where such plant had already been installed for straight " gas-lift " and the wells had passed that stage for producing, it does not seem logical to allow the plant to stand idle and to instal entirely new equipment to produce the wells by means of the mechanically operated plunger pump. Even assuming the displacement pump offered no advantage over the mechanical plunger pump, efficiencies being equal, it would be better to use that plant already installed than to purchase new equipment. The cost of the installation of the compressor plant will have been already partly written off for depreciation, and the plant can be further utilised for producing by the displacement pumping method. The additional expenditure thereby entailed would be a string of tubing, a chamber and an " intermitter " device for each well. The cost would be from $900 to $1200 per 3000-ft. well, depending on conditions and the type of apparatus chosen. The subsequent cost of maintenance and repair would be minimum—in fact, almost a negligible amount.

With regard to the question of efficiency of the mechanically operated pump versus the displacement pump raised by Mr. Ellis and Mr. L. Owen, the writer cannot do better than refer them to a paper by Mr. L. W. Rogers read recently before the Rumanian Branch of the Institution of Petroleum Technologists. The paper

in question deals very thoroughly with short and long-stroke pumps, and gives reasons as to why the displacement pump is undoubtedly superior to the plunger pump, especially in connection with the exploitation of deeper wells.

Referring to Mr. L. Owen's remarks in relation to the "scrapping of an efficiently run mechanical pumping plant in order to instal more up-to-date equipment," the author agrees that this procedure could not be advocated in the majority of cases. Where such plant is in operation on an old-established field, one assumes the field to be of the "stripper" type which could not carry the cost of new equipment. Displacement pumping can be most advantageously employed to follow straight "gas-lift" operations where the field has a comparatively long life before it or is being re-pressured.

Several speakers, including Dr. Henderson, Dr. Wade, Mr. L. Owen and Mr. Ellis, have requested more information in regard to costs of installation, running costs and costs per barrel lifted. It is not within the scope of the discussion on this paper to go into that amount of detail that would be necessary to give actual results of various installations for the purpose of comparison; the writer will give a few figures for their guidance. One thing is obvious: the larger the quantity of oil lifted per well, the higher the efficiency and the cheaper the cost will be. For instance, the relative costs per barrel of oil lifted would be higher for six wells producing 12 brls. each per day than would be the case were the same wells producing 60 brls. each.

It is difficult to quote an average figure based on information gathered from various companies operating on different fields. Results show considerable discrepancy between one field and another, even though operated by the same company. This is attributable to the very varied topographical and sub-surface conditions on different fields. Following are three typical examples:—

Depth of Well, 2300 ft.

Straight "gas-lift."	*Displacement Pumping.*
Producing 125 brls. per day.	Producing 230 brls. per day.
Gas-oil ratio 2,300 per brl.	Gas-oil ratio 1000 per brl.
	Size of chamber, 4½ in., length, 158 ft. 2 in. in 3 in. tubing combination.

Depth of Well, 1300 ft.

Producing 30-33 brls. with 6% fine sand.	Producing 60-70 brls. per day.
Gas-oil ratio, 2,500 per brl.	Gas-oil ratio, 550-660 per brl.
	Size of chamber, 4 in., length, 80 ft. 1½ in. in 2½ in. tubing combination.

Depth of Well, 1400 ft.

By Plunger Pumping.	*By Displacement Pumping.*
35 brls. per day.	75-80 brls.
	Size of chamber, 4 in., length, 104 ft. 1½ in. in 2½ in. tubing combination.

The following figures of the cost of installing displacement pumps in place of the standard pumping equipment have been compiled from records of various companies and represent a fair average :—

Standard Pumping Equipment.	*Displacement Pumping Equipment.*
For 8 wells averaging 2,000 ft. deep :	
$14,056.00.	$14,923.89.
14 Wells averaging 750 ft. deep :	
$11,076.10.	$13,357.51.

The cost of equipping an 80-acre block which is being re-pressured and has high pressure lines already installed is as follows :—

For 8 Wells averaging 2,000 ft. deep $5,371
For 14 wells averaging 750 ft. deep $6,456

The lifting costs per brl. of crude with mechanically operated intermitters are as follows (average) :—

Block acreage.	No. of wells.	Depth. Feet.	Total daily produced in brls.	Lifting cost per brl. U.S.A. cents.
80	14	750	140	0.073
80	8	2,000	80	0.194
80	14	500	90	0·067

It is difficult to estimate the actual saving to be derived by equipping a property with displacement pumps, as the effect is very far reaching and touched practically every department. Less supervision is necessary as the wells are produced almost 100 per cent. efficiently in contrast to a mechanical pumping property where wells are constantly " off " for repairs, cleaning, etc. The Power Plant is central and easily supervised as compared with the multiplicity of small units and mechanical apparatus, all of which require constant attention.

Following are the operating costs of one of the large companies on a repressuring lease :—

Brls. of Pipeline Oil Produced—4100.

Air-Plant Expense.

Operators	$67.50
Chief Tester	$32.90
Repairs	8.25
Fuel Oil	63.55
Lub. Oil	26.13
Total	$198.33

Field Expense.

Pumper	$67.50
Repairs	2.94
Gross prod. tax	121.88
Total	$192.32 or $390.65.

Since the above total of $390.65 includes the expense of repressuring and 75 per cent. of the gas compressed goes to the intake wells, the production costs will be as follows :—

$49+192.32=$241.82 or U.S.A. cents 0.06 per brl.

The following figures show the cost of *converting a mechanical pumping* 160 acre lease with 30 wells, averaging 750 ft. deep., yielding a nett production of 75 brls. per day—*to displacement pumping, and repressuring.*

Average Daily Production per Well—2·5 Brls.	
Well equipment	$4,346
Pressure distributing sys.	3,076
Compressor station	3,895
Labour	1,100
Intermitters	7,500
Equipment of intake pres. wells.. ..	600
	$20,118

Lifting costs by mechanical pumping—	Per day.
2 men well pulling at $130	10
3 pumpers at $130	15
Depreciation	6
3% tax on 75 brls.—2.25 at 60 cts. ..	1.33 or 43 U.S.A. cents per brl.

Listing costs when repressuring and using displacement pumps :—

	Per day.
2 Pumpers at 130 per month	$10
Taxes, 3% on 150 brls., 4.5	2.70
Operating Comp. gas and Lub. oil ..	2.00
Depreciation	6.00
	$20.70 or 14 U.S.A. cents per brl.

Average daily production 5 brls. per well.

It will be noticed that the examples given are all very small producers, and that an allowance for taxes has been included. When exploiting a number of wells with production ranging from 5-12 brls. per day, it is quite impossible to obtain the same high efficiency and low lifting costs as could be accomplished when dealing with wells yielding from 12-60 brls. each per day, or more.

The writer is compiling costs data in respect of deeper wells. As soon as this is completed and he is convinced the figures represent a fair average, he will be pleased to lend them for perusal to any Member interested in such statistics.

Dr. Wade has expressed the wish to know "what would be the effect of displacement pumping upon the paraffin content of the sand in the producing section of a well."

The velocity of flow through the sand will be higher during the earlier stages of producing than later on. This higher velocity combined with the larger volume of gas the oil holds in solution, which lowers the viscosity, will effectually prevent precipitation of paraffin in most cases.

As the producing stage advances, a paraffinous crude will become more viscous owing to less gas being held in solution due to decreased gas pressure. The velocity of the flow of oil through the sand pores is also lowered, allowing paraffin to settle out, which will slowly but surely eventually clog the pores of the producing sand.

The installation of a displacement pump will permit a higher pressure to be maintained on the sand, and the production of formation gas can be greatly reduced in most cases. As explained elsewhere in this discussion, this will result in the oil leaving the sands being richer in light ends, therefore there is less likelihood of paraffin being precipitated.

It is an established fact that the precipitation of paraffin in the flow tubing can be successfully combatted if the flow is so adjusted that it comes within the effective velocity range to suit the particular type of crude being produced.

In other words, there is a velocity for each type of paraffinous crude at which it will not precipitate paraffin, just the same as there is an efficient velocity whereby oil can be lifted together with any sand or mud the well may be making. Should the velocity be lowered, it would result in the sand and mud being precipitated to the bottom of the hole and eventually plugging it. How often is this condition experienced with wells being produced by means of the plunger pump.

Mr. Smith, in discussing the efficiency, states that the " author claimed that 35 per cent. efficiency was easily obtained " ; this is hardly correct, since it was stated " can be attained." The author wishes to make it quite clear that this figure could only be reached under ideal conditions.

Regarding the transmission of power by utilising the oil itself as a hydraulic medium, the author is inclined to believe that not only he, but Petroleum Engineers in general, would welcome any practical data that Mr. Smith could furnish on the subject. A number of years ago considerable attention was given to this means of transmitting power, but little seems to have been heard of the proposed system since. The author would be very interested to learn whether it has been put into practice on any field of importance, and what were the results achieved.

Judging by Mr. Smith's remarks on " gas lift," it would seem that he holds " gas lift " in any shape or form in complete disdain. The best producer of all is undoubtedly a Flowing Well. What is this

but a form of "gas lift"? Instead of the gas being supplied from a compressor, its source is the producing sand, and it can be made to work efficiently or inefficiently, depending entirely on the skill of those in charge. Surely Mr. Smith would not wish us to believe that the utilisation of gas compressed naturally in the sand—as far as efficiency is concerned—" is based on fallacy, supported by false argument, and that its economy is a myth."

Replying to Dr. Henderson, the author wishes to say that he would be only too pleased to give references to literature upon the subject under discussion, but is not aware of any other literature than that mentioned in reply to the President.

The author feels very grateful to Mr. C. A. Andrews for his extreme kindness in arranging to postpone his journey to Germany in order to read the Paper on the writer's behalf, and wishes to thank him for the very able manner in which he fulfilled this task.

He also wishes to express his indebtedness to the Directors of the British Controlled Oilfields, Ltd., in connection with the reading of the paper and their kind permission to use photographs taken on one of their fields for the purpose of illustration.

The paper was also read before a Meeting of the Trinidad Branch of the Institution of Petroleum Technologists on March 30th, 1932, and the discussion which took place is given below :—

Mr. F. H. L. Tindall said gas lift and displacement pumping using compressed gas are by no means new to the oil industry, and were first tried in Trinidad many years ago. Production men can be classified into three main classes :—

Firstly, those who regard gas lift as unnecessary. They maintain that little can be accomplished by gas lift which cannot be done equally well by other methods—chiefly pumping.

Secondly, those who admit that gas lift has a definite use at the end of the " natural flow " period and before pumping need be started. They usually argue that the capital outlay required to instal a suitable gas-lift system is often too large in comparison with the short period of its usefulness.

Thirdly, those who maintain that as soon as a well begins to flow irregularly gas lift should be applied, and that the natural sequence should be " displacement pumping " instead of " beam pumping."

Mr. Millar apparently belongs to the last class, and in his excellent paper has given the theory and practical application of this method of production. The speaker did not agree with all his statements, but he did agree with the principles of displacement pumping.

Mr. Millar stated that with "intermittent gas lift the air or gas is passed down the tubing and the oil flow is up the annular space between the tubing and the casing." This had not been found suitable for their wells, due to the fact that the annular space was too large and too much slippage occurred. They had always applied intermittent gas lift down the casing with the flow up the tubing. It was possible that wells equipped with smaller oil strings might respond better to the other method. In general, he (Mr. Tindall) was not in favour of intermittent flow, due to the pulsating pressures to which the formation was subjected. It had been their experience that intermittent flow had not increased the production of the individual wells, but, with a limited supply of compressed gas available, more wells could be handled by intermittent flow than by direct gas lift, so that the total oil recovered per compressor could be increased.

With reference to displacement pumping, from a theoretical point of view it was definitely superior to beam pumping. The chamber was filled under practically the same conditions as the barrel of a pump, and the difference lies in the method of lifting the oil to the surface. Mr. L. W. Rogers, in his paper read before the Rumanian Branch of the Institution, gave an excellent illustration of the difficulties met with in pumping. Dealing with a pumping well 4400 ft. deep, 2½-in. tubing, ¾-in. rods, 20 strokes per minute, 48-in. stroke, he estimated the following average loads: "Dead load, 14,000 lbs.; impulse load, 18,000 lbs.; unit dead load, 31,600 lbs. per sq. in; unit impulse load, 41,000 lbs. per sq. in.; elastic limit of rod material, 60,000 lbs. per sq. in.; recommended maximum stress, 22,000 lbs. per sq. inch." It would be noted that the recommended maximum stress of 22,000 lbs. per sq. in. was greatly exceeded by the unit impulse load of 41,000 lbs. per sq. in. In the case of displacement pumping the number of cycles would be about 10 per hour or 240 per day. Beam pumping at 20 strokes per minute will require 28,800 cycles per day, a ratio of about 1 to 120. Apart from the wear and fatigue of the rods and tubing, the valves must be considered.

With displacement pumping the standing valve is subjected to a differential pressure of about 250 lbs. per sq. in. 120 times per day. With beam pumping both the standing valve and the travelling valve are subjected to a differential pressure of about 1700 lbs. per sq. in. 28,800 times per day.

The depth of the well makes little difference to pressure exerted in displacement pumping, as the length of fluid in each shot remains fairly uniform. The pressure of 1700 lbs. per sq. in. for a 4400-ft. pumping well would be reduced to about 700 lbs. per sq. in. for a 2000-ft. well. It is obvious that the valves of a pump cannot be

expected to give the same length of service as can be obtained by displacement pumping, and this must be reflected by increased winch work in the case of beam pumping.

From the practical point of view, one is apt to be influenced by the fact that the number of beam pumps in use is considerably greater than the number of displacement pumps. The principle of displacement pumping has been known for a long time, but perhaps its slow adoption should be attributed to lack of suitable equipment rather than to faulty principles. At the present time there are two types of equipment, one controlled by electrical means and the other by mechanical means. They both have their advantages and disadvantages, and it is largely a matter of personal choice as to which can be regarded as the better.

The electrical equipment is expensive and liable to go out of order, due to tubing scale or sand clogging the valves inside the well. It was his experience that scale is continually being formed and loosened from the inside of the 2½-in. and the outside of the 1¼-in. tubing. Its advantages are chiefly :—

1. Small gas per barrel ratio, as the annular space is not vented after each cycle.

2. Electric timing of the wells in rotation so as to have a fairly steady demand for compressed gas.

The mechanical equipment is cheaper than the electrical and has the chief advantage of being all above the surface, and is thus easily repaired or adjusted. Its chief disadvantages are :—

1. Higher gas per barrel ratio as the annular space is vented on each cycle.

2. Inefficient emptying of the flow string due to premature operation of the shut-down valve.

Of the two types on the market at present, he was in favour of the mechanical, but he thought that it can be improved by having a time interval between the closing of the supply valve and the opening of the exhaust valve. He was experimenting with a type of release valve which he hoped would meet the case.

Mr. Millar has given full details as to the capacity of the various sizes of chamber and tubing combinations. The most important feature is the size of the oil string or liner, as this determines the maximum diameter of the chamber which can be run. The next point is the pressure of the gas available.

With compressors capable of high "starting" or "kick-off" pressures, and not fully loaded, this may not be so important, as the pressure will automatically build up until the slug of oil is ejected. With central compressor stations operating at constant pressure, the length of the oil chamber should be chosen so as to leave about 25 per cent. pressure as a safety margin. This will take

care of any overfilling of the chamber due to minor shut-down periods. He suggested 250 lbs. per sq. in. as a suitable operating pressure for central stations, which would allow the chamber and eduction tube to be designed to lift slugs of oil equivalent to about 200 lbs. per sq. in. pressure.

Referring to Table III., and using a tubing combination of 1¼ in. inside 2½ in., it is found that the chamber capacity would be between 5 and 6 cu. ft.—*i.e.*, about 1 barrel of oil. Turning to Table I., 60 ft. of 4-in. line pipe would give the required capacity. In making up the three joints of 4-in. pipe it may be found advisable to thread the 4-in. with female thread and make short connecting nipples of male thread. This does away with the extra diameter of the 4-in. collars, and allows the chamber to be run through tight places in the casing. Care should be taken that the connecting nipples are rounded off to prevent the inner string from holding up. With properly designed chambers and tubing combinations, it should not be necessary to use "booster" holes in the eductor string.

After running both strings of tubing in the hole, it will usually be found that there is too much oil to allow flow to start. He had made a useful starting device. It contains two ¼-in. holes placed about 300 ft. from the bottom of the 1¼-in. pipe. Normally the holes are closed, but, if the tubing be raised a few inches, the holes are opened. This allows aeration to begin, until eventually the gas will force its way around the bottom of the 1¼-in. The 1¼-in. is run through a stuffing box at the surface so that it can be raised or lowered without loss of pressure. If the level of the fluid is so high that those holes are still covered, the tubing is lifted a little further so that the standing valve is raised from its seat. The pressure of the gas in the annular space will then force some of the oil through the standing valve out of the chamber into the casing. As the area of the casing is much larger than that of the tubing, the fluid level in the tubing can be lowered considerably, and flow established. The total lift is only about 9 ins., and it will be found useful to fit clamps to the 1¼-in. pipe under a collar on the surface and rest the clamps on two screw jacks. This serves to support the 1¼-in. for normal conditions and does away with the use of a winch for lifting purposes. Should the well stop flowing for any reason and build up too much oil, to start up again, it is a simple matter to make a few turns of the jacks to start the well. The flow line should be equipped with about 6 ft. of flexible hose to allow movement without strain.

With reference to results, the experience of the speaker had been greatly limited owing to rigid curtailment of production requirements and other economic measures. A mechanical device was

lent to us in 1930 and was used for four days on a well 350 ft. deep. At that time it was necessary to run a "starting pipe" down the well outside the two strings of tubing. As this was regarded as a most hazardous procedure, the equipment was not looked upon very favourably. There was little opportunity for fine adjustment, but the production of the well was increased from 32 barrels per day to 52 barrels per day, and the gas in per barrel lifted was about 650 cu. ft. Later on another well was equipped with a water bucket and siphon which operated two ½-in. lubricated stop cocks. The results obtained were good, and the well produced about 20 barrels of oil per day for ten months. The gas in per barrel averaged about 2000 cu. ft., but was purposely kept high to prevent compressor failure causing a permanent shut down. Recently experiments with similar equipment have been started, and appear to be satisfactory, but as the wells had been standing idle for nearly six months, he would not like to quote any figures until they have settled down to steady production.

The metering of the gas consumed per cycle is a difficult problem, owing to the very irregular nature of the gas flow, but the following calculation will show that the gas required per barrel of oil lifted must be reasonably low. In a well 2000 ft. deep, equipped with 1½-in. tubing inside 2½-in. tubing, the volume of the annular space if about 35 cu. ft. It will require 583 ft. to fill this space with gas at 250 lb. per sq. in. If a chamber of 1-barrel capacity be installed, only 874 cu. ft. per barrel will be required for 75 per cent. chamber efficiency and 1166 cu. ft. per barrel for 50 per cent. efficiency. It was found that, with direct connected gas-engine driven compressors, the actual operation cost of compressing gas can be kept below 2 cents per 1000 cu. ft. (This does not include depreciation or interest on the capital investment.) Allowing for leakage and pipe-line maintenance, it seems probable that the actual lifting costs for displacement pumping can theoretically be kept within the region of 3 cents per barrel. Time alone will show how close we could come to this in practice, but he was of the firm belief that money spent on experiments in connection with displacement pumping could be regarded as a sound investment.

It is only natural that the first few wells will require considerably more attention than can normally be given to individual wells, but once the experimental stage has passed, he was sure that wells equipped for displacement pumping will require less costly attention than those equipped for beam pumping.

Mr. A. H. Richard said there was one point he would like to refer to, that was with regard to the recovery of gasoline from the gas which was used for lifting. Mr. Millar mentioned that air could take up half a gallon of gasoline per 1000 cu. ft. from the oil.

Of course, it was obvious some gasoline would be taken up from the oil; it might be a small or it might be a large amount, that depended a good deal on the quality of the oil to be lifted. The greatest gain from the lifting operations would, therefore, be obtained by running them in conjunction with a gasoline recovery plant. In general, gasoline could be profitably recovered from practically all gas used in lifting.

Of course, in displacement pumping, as Mr. Millar mentioned in his paper, the gas which was in direct contact with the oil would be the richest in gasoline and the remainder might not take up anything to speak of. It was quite possible to arrange that the gas which immediately followed the slug of oil could be taken into the suction lines to the gasoline recovery plant, and the remainder of the gas which was practically dry could be returned to the lean gas lines or it could be wasted. In fact he had seen a single regulator described which performed these functions.

Mr. P. Meyer enquired whether the half a gallon of gasoline per 1000 cu. ft. contained in the gas after displacement applied to the gas as a whole or only to the first surge; and whether any member present at the meeting could give typical figures for the gasoline content at the first surge and at the end of the cycle.

Mr. J. W. Hardy said that Mr. Millar seemed to be too optimistic in some of his figures.

He suggested using riser tubing with diameters from ½ in. to 1½ in. Half an inch for a riser tubing seemed very small indeed, particularly if the oil was anything as thick as it was on the Forest Field. He would have thought the friction much too high due to viscosity.

The author said the velocity in the riser tubing was 128 ft. per second, and in all probability that had been exceeded in practice. It seemed to him that the frictional head on a column of oil at a velocity of 128 ft. per second was very high indeed. Later on in the paper he said 8 to 25 ft. per second would be most efficient, and yet he gave an actual case of 128 ft. per second. It seemed a wide variation in that case.

Mr. L. A. Toone asked if Mr. Tindall had any experience of electrical timing apparatus for which direct current had been used instead of alternating current.

Mr. J. P. Potter said that they had tried out displacement pumping not only on small producers but on wells which had not been capable of being produced by any other method. In the case of small pumpers the production had gone up 70 to 80 per cent. and those wells which they were unable to produce by pumping for mechanical reasons, *i.e.*, crooked holes, bad sand conditions, etc., were now steady producers.

There was one thing about Mr. Millar's paper that he would like to emphasize, that whereas straight gas-lift, however useful it might have been, could only be used for an intermediate period in the life of a producing well, that was, from the time the well stopped flowing until the time when it was ready to be put on the pump, the displacement pump could be installed and left in the well until no more oil could be extracted. There was never any need to consider the installation of a plunger pump.

Mr. C. E. Capito said he thought Mr. Millar had done a very useful act in bringing this subject up not only to the local Branch, but to the Institution at home.

It seemed to him that a great deal of difficulty in producing from crooked holes and from deep wells would be entirely eliminated by the displacement pump. Even if the subterranean electrical centrifugal pump ever got working properly there would still remain the large head of oil on the top of the standing valve and against which the pump would have to be started. These factors were eliminated with the displacement pump, as the chamber could be immersed to any maximum depth.

He thought possibly the chief economy in displacement pumping was the lack of pulling. He had personal experience with this economy in Assam 22 years ago when he persuaded the Company there to give him a compressor for straight gas lift, and he found that whereas before he had the compressor he had abour 3 or 4 individual pumpers, 2 pumping powers, several pumpmen and 3 pulling gangs, after the change over he had a man running the compressor, another man going round opening the valves and one pulling gang which showed a pretty fair economy in staff. The only thing he did not do, he never thought of putting a chamber on the bottom of his tubing. He tried all sorts of combinations, concentric tubing, tubing side by side, which he would not advise anybody to try, and running down inside the well with a small air line, using the oil string as the eductor pipe, and he got very little difference in production. But by running a half-inch air line down several of the old wells which did not pay to pump he was able to get paying production from these by blowing them every now and then.

Mr. A. F. Dabell said that the promise displacement pumping presented was that air or gas lift could be used in wells without pressure being applied to the face of the producing sand, and it would be interesting to learn from anyone who had replaced straight gas lift by displacement pumping the degree of improvement resulting therefrom, otherwise, he was of the opinion that displacement pumping showed to advantage only during a transitory critical period in the history of a well of normal character.

His personal experience with the displacement pump was confined to 7-inch diameter wells of 1200 ft. depth, which yielded under plunger pumping some six or seven barrels per day and identically the same over a 20–25 day test with a displacement pump.

Given that the foot valve upon the tubing of a plunger pump and a displacement pump be at the same depth, a well which has an inflow of oil equal to or in excess of the capacity of the former should show to advantage when operated by the latter, but when the level of the liquid being pumped falls to the level of the valve then the plunger pump should do better.

The reason for this is that in plunger pumping the liquid is never allowed to accumulate and retard inflow, whilst displacement pumping is dependent upon alternating accumulation and exhaustion. Alternatively, they must grant that the pressure of liquid upon the face of an oil sand has no retarding effect on the influx of oil.

The declaration by the author that "the overall efficiency of the displacement pump starting from the b.h.p. of the prime mover driving the compressors on the one hand to the work accomplished in lifting the oil on the other hand can be as high as 15 to 20 per cent.," is misleading. The test he had made showed an overall efficiency of 0·3 per cent.

Incidentally, it was to be regretted that it was necessary to give study to the recovery of oil by extraneous power, but it was comforting to note the optimism prompting the suggestion that future economic conditions would permit artificial methods of stripping oil from the sand after the flowing stage was passed.

Greater promise lies in study of methods for obtaining greater recovery from wells during the natural flowing period.

Mr. C. R. Massy said that Mr. Tindall had complained of a premature shut-down, causing improper emptying of the chamber and scavenging of the production tube in connection with the use of "mechanical control." He was using an aerating orifice in the eductor tube, and it was the speaker's experience that, in most cases where this aerating orifice had been used, the condition complained of had prevailed. The speaker had come to the conclusion that where the diameters of the eductor tube and length and diameter of the chamber were correctly proportioned there was seldom need for an aerating orifice except in very special cases. The use of an aerating orifice had been suggested by the makes of both the "Mechanical" and "Electrical" control; he thought, however, that before long they would be inclined to revise their recommendations.

The use of the aerating orifice, he thought, had been introduced with a view to aerating the fluid column in the eductor tube, where the operating pressure available was insufficient to support the full contents of the chamber when displaced into the flow-pipe. He disagreed with the benefit to be thus obtained in most installations, since, unless the column in the eductor tube could be aerated sufficiently to cause it to overflow at the surface, no reduction in pressure would be obtained in the lower end of the flow pipe.

Let it be presumed that the chamber be 100 feet long, and that the relative internal diameters of the chamber and eductor be such that the oil when displaced from the chamber would rise 600 feet into the eductor tube, and that the specific gravity of the fluid be such that 240 lb. pressure be required to support this column of fluid. It becomes evident that if an aerating orifice be introduced in the eductor tube, and the column therein be aerated, no decrease in pressure in the eductor tube at that point will be obtained, unless the aerated column be caused to overflow at the surface, and this condition is likely to prevail in only very shallow wells.

The pressure required to support a 500 foot column of dead oil in the eductor tube would be the same as the pressure required to support the same amount of oil, even though it be so aerated as to attain a height of 1000 feet or more.

He felt certain that in the case of the installation to which Mr. Tindall had referred he would obtain better results as soon as he eliminated the aerating orifice, which he understood Mr. Tindall intended to do.

Mr. F. H. L. Tindall, in closing the discussion, said anent Mr. Richard's remarks about the richness of the gas and also Mr. Millar's about half a gallon of gasoline per 1000 cu. ft., they had found in dealing with direct gas-lift that their gas only contained half a gallon of gasoline per 1000 cu. ft., so that there would not be much difference between the two.

He was interested to hear about the regulator which would automatically take the rich gas into one system and lean gas into the other, Such an installation, however, might make the cost of installation per well too high.

Mr. Hardy raised a point in regard to a velocity of 128 ft. per second for a slug of oil. Personally he thought that extremely high. A slug of oil rising through 1¼ in. diameter tubing at 128 ft. per second would have considerable momentum and would need some very strong fittings on top of the 1¼ in. tubing.

In regard to Mr. Toone's reference to electrical equipment they had only used the sub-surface equipment, and had had no experience as to the merits of direct or alternating current for the surface equipment.

Mr. Capito had said that winch work could be definitely decreased by the application of compressed gas in one form or another. In their case they could not very well bring forward figures that winch work had been reduced, as they had dealt with special wells which had been taken straight from the natural flow period and which would require little winch work, no matter how they were produced. The practical proof that Mr. Capito had was in favour of Mr. Millar's paper, where he maintained that winch work could be reduced by displacement pumping.

In regard to Mr. Dabell's point with reference to the ill-effect of the presence of air on an oilsand, he thought in general the sand would possibly produce more oil if it was in contact with oil than if it was in contact with gas or air held under back pressure.

He was very much in accord with Mr. Massy in regard to the aerating orifice.

Mr. Albert Millar, in reply, wrote: In answer to Mr. A. H. Richard and Mr. P. Meyer, the half-gallon saturation per 100 cu. ft. of air was found to be the maximum saturation of that portion of the ejecting air that came into contact with the slug of oil lifted. With a well using 1000 cu. ft. per cycle, probably less than 100 cu. ft. would contain 0.5 gal. per 1000 and 900 cu. ft. would contain almost nothing at all.

It had been found that it did not pay to collect low-pressure exhaust gas containing probably less than 0.3 gal. per 100 cu. ft. for gasoline extraction. If rich gas from high-pressure oil-gas separators is used for lifting, it is possible that the gasoline content of the gas would be such as to make gasoline recovery practicable and advisable.

It would be advisable in every case where displacement pumping is being installed to very carefully test the gasoline content of the exhaust gas before any money is spent in laying a collecting system.

In reply to Mr. J. W. Hardy, the $\frac{1}{2}$ in. riser tubings are being used on shallow wells producing a light crude oil. When selecting the tubing combination, one must give due consideration to all the governing factors, which would naturally include viscosity. With regard to the riser tube velocities, the figures of 8 to 25 ft./sec. quoted in the paper are average velocities.

There are at least three distinct velocity periods. The first is when the lifting air or gas enters the chamber at high pressure and velocity, and the pressure differential between the chamber and

the riser tubing is at its maximum. It is at this moment that the highest velocity in the riser tubing occurs, and initial velocities can easily attain 100 to 200 ft. per second with light oils of low viscosity. As the length of the column of oil increases in the riser tubing, the velocity will decrease, and it is at this point that the flow velocity may become critical if the running pressure is too low or the inflow of the lifting gas is restricted. The third period is when the top of the column of oil being lifted has reached the surface; the load is then a diminishing one and the velocity again increases.

The Strobophonometer.

(A method of comparing and locating knock and other engine and machinery noises.)

By R. STANSFIELD, A.M.Inst.C.E. (Member) and R. E. H. CARPENTER.

The use of valve amplifiers in conjunction with a microphone and a suitable indicating meter for the comparisons of noises emitted by running machinery under various conditions is not novel, and reference to apparatus of this description has appeared from time to time in the technical Press.

In a paper read by Huf, Sabina and Hill[1] an "audiometer" was described in connection with the measurement of the knocking tendencies of motor spirits in a single-cylinder spirit-testing engine, and a number of experimental curves were given showing the response of the output meter of the apparatus to change in the fuel.

Recently there has been an increased interest shown in this method of knock measurement, especially as road tests now being made in America have indicated that the usual slow-running speed of many laboratory spirit-testing engines is one of the possible causes of results not being in sufficient agreement with road behaviour. As far as it has been possible to analyse the figures so far obtained, it seems that considerably higher running speeds will be necessary for the test engines if good agreement with road performance is to be obtained. This involves either redesigning the bouncing-pin indicator so that it will operate satisfactorily at speeds above its present upper limit of about 900 r.p.m. or using a new type of apparatus for indicating the degree of knock. For this class of work the electrical method appears to offer valuable possibilities.

If an observer be asked to give his opinion of the incidence of knock in a petrol engine when the conditions are changed from smooth running, through rough, to the detonating stage, he will invariably reply that the knock has introduced a new high-frequency note, with very little change in the other already existing audible frequencies. It is probably a result of this opinion that most phonometer developments for knock testing have included a frequency filter designed to pass only the higher frequencies above, say, 2000 to 3000 cycles per second. While these frequencies are certainly those which most influence the ear on account of

[1] Effect of Sound Intensity on Knock Ratings. *J.S.A.E.*, 1931, **29**, 134-136.

their relatively large amplitude while they last, frequency selection, in the Authors' experience, does not in fact increase appreciably the differential sensitivity of the method for knock-testing purposes.

In order to insure that the true conditions were fully understood, preliminary tests were made on three engines of widely different types, using a good carbon microphone as the receiver, and a valve amplifier which included a tuneable frequency selective voltmeter. In this way the entire sound spectrum from about 200 cycles per second up to 10,000 cycles per second was explored. A curve of sound intensity against frequency was plotted for each engine in the smooth-running condition, and then for each under knocking conditions. A series of peaks, generally descending in height with rise of frequency, was found to exist for both types of running, no *new* peak being introduced with change from smooth running to audible knock. Two of the engines showed the greatest change of sound in the region of 2000/2500 cycles per second, while the third showed the most marked change at only 800 cycles per second, although, to the ear, a much higher note knock sound had developed in the latter case than in the two former. In addition to locating the peak values most affected by the change of running conditions, it was found that nearly all the other peaks on the smooth-running curve had increased in height when knock developed, showing that detonation was affecting the entire sound spectrum. The increase of sound in different portions of the spectrum varied between about 5 and 10 per cent. for a change in fuel octane number of 4.

It became clear from these tests that the failure of the phonometer to respond to the audible increase in the higher frequencies was due to the fact that the meter averaged the sound over the whole time period, whereas the ear and brain were able to apply selective attention to the isolated recurrent pinking sounds.

One disadvantage of the usual electrical listening methods is that they readily respond to any other sounds in the cycle, and also to sounds from other sources in the vicinity of the engine. This makes high accuracy difficult to obtain, especially with a noisy engine or in the many cases where the plant under test cannot be isolated.

These difficulties have been overcome by an apparatus which the Authors have named the Strobophonometer. It is an instrument for the analysis and measurement of sounds or vibrations emanating from any source in cycles. It applies to sound from an engine or other machine a principle analagous to that of the Stroboscope ; that is to say, it selects, on a time basis, some part of a recurrent noise to be investigated. The relative intensity of this noise is arranged to be indicated on a meter. The length of the listening period in degrees of cycle, and the phasing of this period round the

cycle of operations, can readily be adjusted when necessary, and the use of a relatively short listening period makes external noises unimportant.

For the majority of applications a simple telephone earpiece is highly satisfactory as the microphone. When this is held in a sponge rubber mounting against the source of sound the diaphragm is damped by the air pocket formed between the machine, the rubber, and the diaphragm housing. This damping is sufficient to give the necessary frequency range, and the range may easily be changed when required. As has been explained above, the selection of high frequencies only does not appear to be of value in most cases, and may definitely be harmful. If necessary, however, diaphragms of various thicknesses held near to the machine, but not enclosed to give air damping, may be substituted, the thickness being such as to respond to a desired frequency. Alternatively an expensive and delicate microphone having a flat response, and used with or without a frequency filter, may be adopted for special work. After many tests with microphones of varying excellence, the Authors have only found it of advantage to depart from the simple earpiece with a thin diaphragm to one of heavier gauge in the case of multi-cylinder engines. In these, each cylinder is giving its quota of noise, and the disadvantage of the low response of the thick diaphragm and the small energy component of the high-frequency noises is reduced on account of the number of cylinders emitting similar sounds during a complete working cycle. Flat response microphones have shown surprisingly little, if any, gain in relative performance for any application.

Operation of the amplifier from any of the usual alternating current supplies is obviously the simplest for general use, since this eliminates bulky high tension accumulators and low tension battery, together with the need for keeping these charged. The A.C. input transformer can be coupled to operate from any mains voltage by adjustment of connections, and a portable arrangement is possible by the use of a 12-volt car starter battery and a small 12-volt D.C. motor coupled to a suitable A.C. generator with much greater convenience than if a D.C. system is used direct.

The only objection to the A.C. amplifier is its higher cost where D.C. is already available, and to meet such cases an alternative D.C. operated model has been designed.

Fig. 1 shows the complete apparatus for A.C. use, the separate units consisting of the microphone, the amplifier, the output meter and control box, and the selector. Externally the D.C. model differs only in that the output meter box is dispensed with, and the meter and controls are housed with the amplifier in one casing.

The general design of such an amplifier to avoid mains hum and objectionable variation of sensitivity with variation of mains voltage is a matter requiring considerable care. It must also be remembered that if a listening period of, say, one-thirtieth of the cycle is the minimum to be used, the valves have to be capable of dealing with a voltage at least thirty times that which will give the desired meter reading if applied continuously. Mains hum quite tolerable in a good radio receiver may give a large scale deflection on the output meter, and thus special arrangements are required

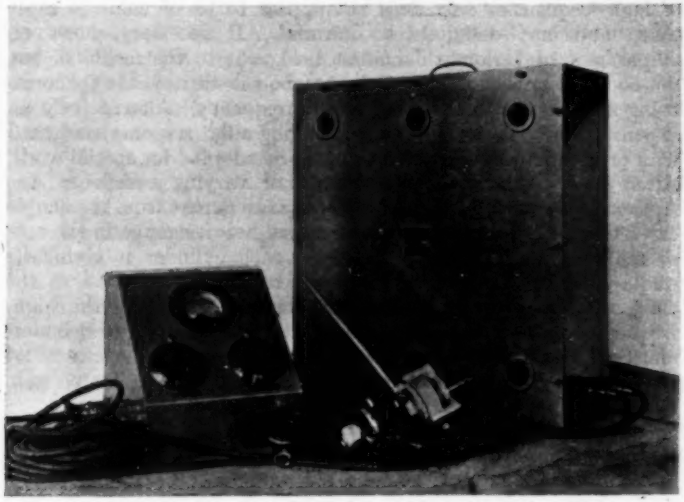

FIG. 1.

CARPENTER-STANSFIELD STROBOPHONOMETER.

to keep the zero level from hum down to the minimum. When a full cycle of noise is examined the zero due to hum has been reduced to not more than 2 per cent. of full scale reading, and as the listening angle is reduced this falls proportionately.

Since engine noises are never exactly repeated from cycle to cycle, and also since any sound measuring apparatus should be as wide in application as possible, it is necessary to provide means for damping needle fluctuations, and such means should be adjustable over a wide range of values. A suitable damping control, operating electrically, is mounted alongside the sensitivity control, and when this is in full action the meter needle takes about 7 seconds to halve

its deflection after the microphone is disconnected. This degree of damping is sufficient to give a good steady reading with noises occurring at any machine speed above the limit at which the ear can readily detect the actual phasing. If successive sounds are not of the same intensity an averaging effect is obtained, the reading being very nearly the arithmetic mean of the individual values. If necessary the meter may be designed so that it gives approximately the R.M.S. value of varying sounds, or an extra stop may be fitted to determine maximum values.

As regards the selector, this is to be driven from the machine under examination, and is provided with a direct and a two-to-one geared drive so that it can be used on four-stroke cycle engines coupled either to the cam shaft or the crank shaft. Two knurled nuts on the selector release the brush gear controlling the listening angle and the phasing, and allow either of these to be adjusted at will.

The entire apparatus is designed with a view to general use in a test house or workshop where rough handling is to be expected, and all the connecting cables are metal sheathed under a woven covering. The first complete unit has now been in use for upwards of 700 hours, and has not required the slightest attention.

Turning now to the applications of the instrument in greater detail, it will be obvious that the introduction of the selecting mechanism enormously increases the field of usefulness compared with any sound measuring apparatus which is arranged only to listen to the entire cycle of sound, or only to a given frequency range. Consider the simple case of a noisy pair of gears. The noise may be due to the teeth being generally too deep in mesh, or it may be a varying noise due to one of the shafts or wheels running eccentrically. The simple form of phonometer registers the mean noise in each case, and cannot distinguish between the two types. The present apparatus, on the other hand, may be used to determine the relative total noises from a series of gear assemblies used without the selector. It may be used in conjunction with the selector to determine whether noise from an assembly is constant throughout a revolution of any shaft, or whether it varies with the angle turned through on account of eccentricity. It also locates a sound caused by a single bad tooth. For the latter purposes the selector is coupled to a suitable shaft and set so that the listening angle is, say, 30 degrees, and this period is then phased round the cycle. If the noise is steady the output meter reading will remain constant. If it varies, due to eccentricity, then the reading will alter steadily between a minimum and a maximum, or through a series of maxima and minima if the driving shaft is running more slowly than the eccentric shaft, the positions of the low and high values

indicating the points of lightest and heaviest mesh. If the noise is local, then the meter reading will alter suddenly each time the badly formed or damaged tooth comes into mesh.

In the case of knock noises from engines it is possible to compare combustion sounds with other mechanical noises, and so to determine the relative importance of each in making up the total running noise. One such examination of a single-cylinder high-speed Diesel

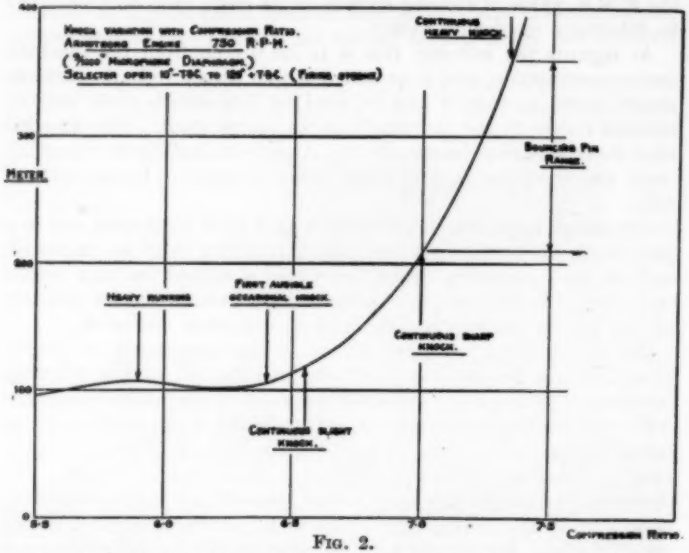

FIG. 2.

engine showed that the noise from overhead valve gear was much more serious than the combustion shock on an average fuel. In a second example the combustion shock was more pronounced than any other sound. The total sound level from the two engines was roughly the same. The value of such data to the designer is obvious.

Fig. 2 shows a diagram taken from a single-cylinder variable-compression engine used for testing motor spirits. The record in this case is of the noise during the expansion stroke from top dead centre to the opening of the exhaust valve. Smaller listening angles give the same relative results, but require more opening of the sensitivity control, and, in the limit, will not give a sufficient scale reading except for the loudest noises. If the angle is prolonged, the noise of the exhaust may be introduced and thus reduce any alterations occurring during the firing stroke alone. Generally it is found

best to use the longest possible angle of listening provided it does not include more than one major sound. The test of Fig. 2 was made with the engine running on a spirit which allowed smooth operation at a compression ratio of 5·5 to 1. Starting from this ratio, the compression was increased and meter readings taken at every increment of 1/10th ratio. It will be noticed that the noise first increases slightly with heavy running. After this stage there is a slight drop in noise but still no audible knock. The drop may be due to the shape of the combustion chamber, which is altered in form with increase of ratio by reducing the length of a pocket of small bore. Following the heavy running period, the meter reading begins to rise sharply, and the first faintly audible and intermittent knock commences. The meter reading has risen about 20 per cent. above the smooth-running level by the time the knock is continuous but slight, and at this intensity it is possible to distinguish easily between fuels of different anti-knock value. By the time the bouncing-pin electrolytic cell gives 0·2 cc. of gas per minute, the scale reading has increased more than 100 per cent. from smooth running. The range of meter readings covering the usual bouncing-pin range of knock is shown on the diagram, and much heavier intensities can be explored if desired, up to the point where pre-ignition may damage the engine.

So far no difference of importance has been detected between fuel ratings by means of the Strobophonometer and those taken with a bouncing-pin used in the same engine, neither has any appreciable difference been noted between results taken with very light, average, and heavy knock, provided that pre-ignition is not present.

Those familiar with spirit testing will recognise several advantages of the listening method over the bouncing-pin. The knock intensity can be much more in agreement with the knock occurring on a car ; the engine speed can be increased to any desired value to obtain better agreement with road practice ; much more rapid testing is possible since it is only necessary to wait between readings until the change-over lag from one fuel to another is established, and the end of this lag period is clearly indicated ; surges in the meter readings are not connected with the measuring apparatus, and therefore show the need for cleaning the engine itself, or attending to the ignition system ; in engines with a relatively low upper limit of compression ratio the use of a lighter knock makes it easy to test fuels of 10 or more octane numbers higher rating than is possible with the bouncing-pin in the same engine ; no special boss is required for coupling the instrument to the combustion space such as is necessary for a bouncing-pin diaphragm, and hence risk of hot spots is reduced, and a standard type of combustion chamber is maintained.

Knock on multi-cylinder engines may be examined at engine speeds up to about 1500 r.p.m. without any modification to the standard microphone, even when running is very noisy. In this application the selector is phased to listen to the early part of the expansion stroke of any desired cylinder, and the angle chosen so that no major noise from another cylinder occurs at the same time. Since the level of noise from the other cylinders affects the meter reading, the response to change of knock in the cylinder under inspection is less than for a single-cylinder engine, but a higher response is not of much advantage because there is much more general surging with a multi-cylinder engine. This means that a limit is set to experimental error on account of engine variations, and hence a lower response is ample to suit the characteristics of such engines.

An alternative method for multi-cylinder engines is to fit a special selector commutator which allows of listening to, say, 30 degrees of each firing stroke, and to use a microphone about 0·045 in. thick. This gives time and frequency selection, and the meter integrates and averages the knock from all the cylinders. The best position of the listening angle with relation to the crank is that which reduces the other cyclic noises occurring during the listening period to the minimum, and is rapidly found by trial.

In order further to show the importance of the selector mechanism, Figs. 3 and 4 have been taken from a single-cylinder engine running on two spirits differing by 4 octane numbers, the knock being inaudible on the better fuel, and just audible on the poorer. In these tests the listening angle was 30 degrees, since it was desired to show the peak value of certain sounds sharply. The listening angle was phased round the cycle so that all the major noises were examined in turn. The abscissæ of each diagram represent the position of the listening angle in the cycle, and the ordinates represent sound. The microphone was held against the upper portion of the cylinder wall, and the engine was entremely quiet as regards mechanical noises. It will be seen from Fig. 3 that the effect of change of fuel is noticeable only when the listening period occurs during the expansion stroke, and that the change of reading with change of fuel is fairly constant over a wide phasing angle. The peak value does not necessarily occur at the position where the listening angle begins at top centre, this being partly due to averaging effects over the whole listening angle, partly to lag caused by the natural period of the microphone diaphragm, and partly to the fact that the major noise may be due to interaction between the wave producing the knock and the mechanical inertia of a series of parts of the engine structure. The remaining peaks on the curve are due to muffled exhaust noise and piston slap. If it is

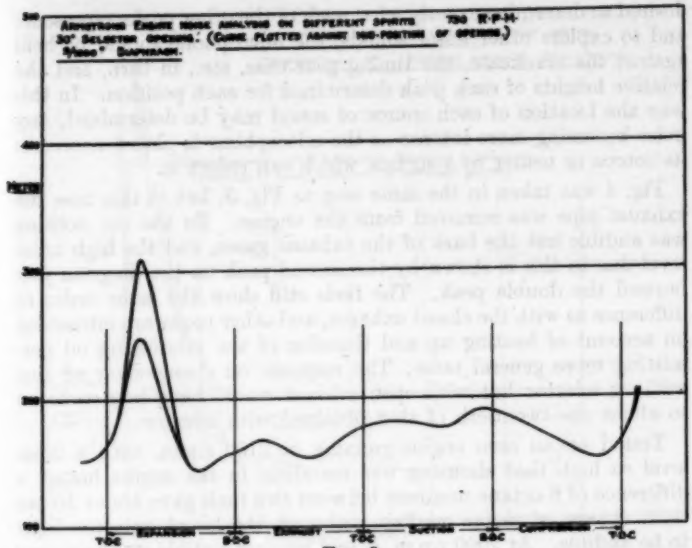
TDC
EXPANSION
BDC
EXHAUST
TDC
SUCTION
BDC
COMPRESSION
TDC

FIG. 3.

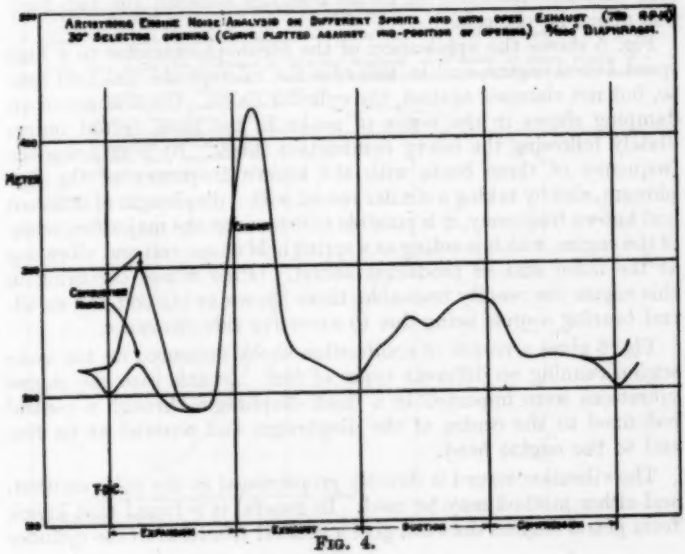
EXHAUST
TDC.
EXPANSION
EXHAUST
SUCTION
COMPRESSION

FIG. 4.

desired to determine exactly what each of the other peaks represents and to explore other lesser sounds, the microphone should be held against the crankcase, the timing gear case, etc., in turn, and the relative heights of each peak determined for each position. In this way the location of each source of sound may be determined, any noise becoming more intense as the microphone is placed nearer to its source or nearer to a surface which can reflect it.

Fig. 4 was taken in the same way as Fig. 3, but in this case the exhaust pipe was removed from the engine. To the ear nothing was audible but the bark of the exhaust gases, and the high noise level due to this is shown by the second peak on the diagram just beyond the double peak. The fuels still show the same order of difference as with the closed exhaust, and other peaks are intensified on account of heating up and thinning of the lubricating oil permitting more general noise. The response on change-over of fuel without selector but with open exhaust would have been reduced to about one-twentieth of that obtained with selector.

Tested on an aero engine running at 2100 r.p.m. with a noise level so high that shouting was inaudible in the engine house, a difference of 6 octane numbers between two fuels gave about 10 per cent. change of meter reading, although the knock was too light to be audible. At 2000 r.p.m. it just became audible on the poorer fuel, and the difference in meter readings between the two fuels was about 20 per cent.

Fig. 5 shows the application of the Strobophonometer to a high speed Diesel engine, and in this case the microphone was held near to, but not clamped against, the cylinder block. The absence of air damping shows in the series of peaks in the noise record immediately following the heavy combustion shock. By comparing the frequency of these beats with the known frequency of the diaphragm, and by taking a similar record with a diaphragm of different and known frequency, it is possible to determine the major frequency of the engine, which is acting as a spring held at one end and vibrating at the other and so producing sound. Other noises occurring in this engine are readily traceable, those shown as big-end and small-end bearing sounds being due to excessive side clearance.

Fig. 6 gives a record of combustion shock measured on the same engine running on different types of fuel. In this case the engine vibrations were imparted to a thick diaphragm through a central rod fixed to the centre of the diaphragm and screwed at its free end to the engine head.

The vibration record is directly proportional to the noise emitted, and either method may be used. In general it is found that knock from petrol engines does not give a general vibration to the cylinder

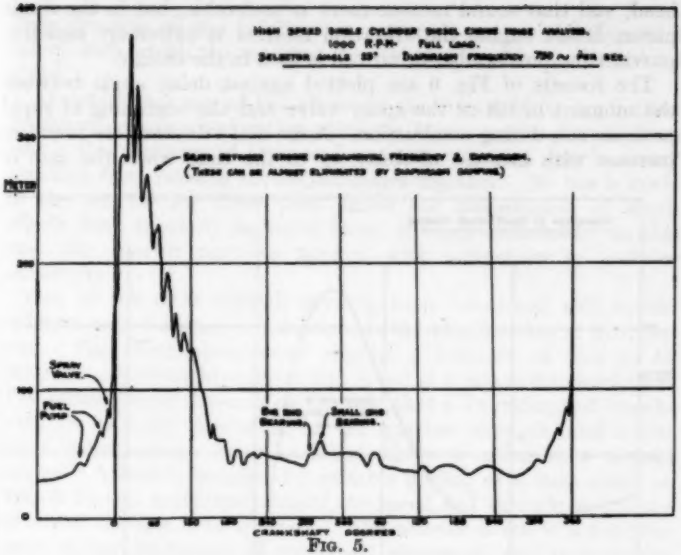
HIGH SPEED SINGLE CYLINDER DIESEL ENGINE NOISE ANALYSIS.
1000 R.P.M. FULL LOAD.
DIAPHRAGM FREQUENCY 750 ∿ PER SEC.
SPRAY VALVE.
FUEL PUMP.
BIG END BEARINGS.
SMALL END BEARINGS.
CRANKSHAFT DEGREES

FIG. 5.

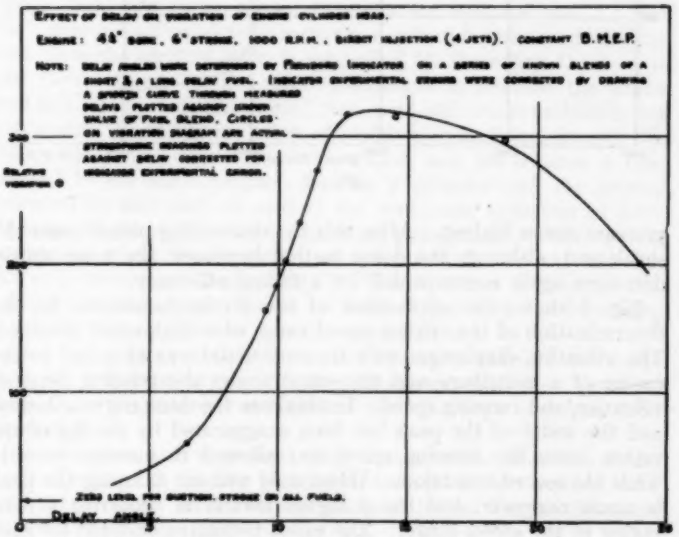
EFFECT OF DELAY ON VIBRATION OF ENGINE CYLINDER HEAD.
ENGINE : 4½" BORE, 6" STROKE. 1000 R.P.M. DIRECT INJECTION (4 JETS). CONSTANT B.M.E.P.
DELAY ANGLES
ZERO LEVEL FOR SUCTION STROKE ON ALL FIELDS.
DELAY ANGLE

FIG. 6.

head, and that sound measurement is preferable, but in the single piston Diesel engine the vibration method is extremely sensitive provided no prechamber or air cell is used in the design.

The records of Fig. 6 are plotted against delay angle between the moment of lift of the spray valve and the beginning of rapid pressure rise during combustion. Noise and vibration are found to increase with increase of delay up to the time when the rate of

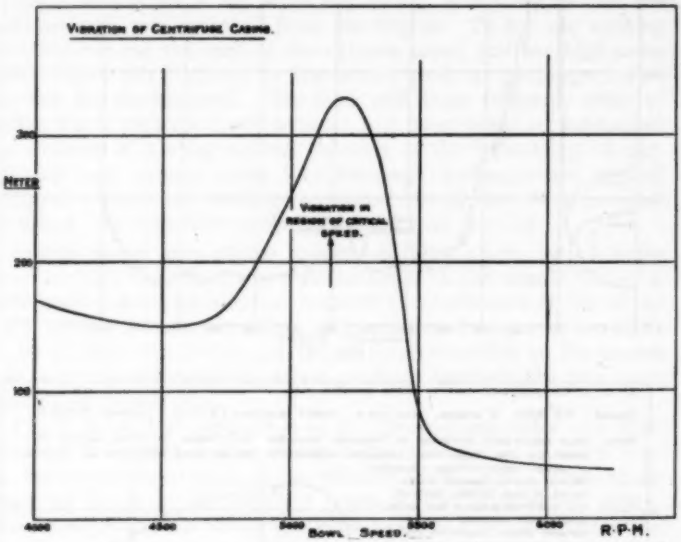

Fig. 7.

pressure rise is highest. After this the descending piston eases the shock and, although the delay further increases, the noise slowly decreases again accompanied by a falling efficiency.

Fig. 7 shows the application of the Strobophonometer to the determination of the critical speed range of a high-speed machine. The vibration diaphragm with its central rod was attached to the casing of a centrifuge and the curve shows the relation between vibration and running speed. In this case the damping was heavy, and the width of the peak has been exaggerated by the lag of the meter, since the running speed was allowed to increase steadily while the record was taken. When used without damping the peak is much narrower, and has a higher maximum occurring a little earlier in the speed range. The exact technique adopted for such

tests depends on the information required, and on the degree of safety with which the machine may be run steadily at the critical speed.

An interesting use of the vibration diaphragm is its application to the mapping of vibration contours in an engine house, from which the positions of least and greatest vibration can be found resulting from running several machines together. No use is made of the selector for these tests unless the transmission of shock effects from regularly repeated blows is being examined. In this case the selector may be applied with advantage to increase sensitivity.

One of the most difficult investigations connected with multi-cylinder petrol engine performance is the examination of distribution. The Strobophonometer enables a measure of this to be taken at any throttle position and speed in a relatively short time. The method used depends on the fact that a knocking fuel knocks with an intensity depending on the mixture strength, and is but little influenced by other variables likely to occur in a normal engine. A fuel is blended by suitable doping of a base spirit so that it knocks moderately under the speed and throttle conditions at which the test is to be made. The selector is set to a listening angle of, say, 30 degrees of crankshaft movement, and to cover the range from top firing centre forwards for cylinder No. 1. The carburettor is adjusted to be rather richer than for standard running, and then the air/fuel ratio is controlled by throttling the feed to the carburettor. As the mixture strength is reduced the knock will first rise to a maximum and then, with still weaker mixture, will fall again. Readings are taken of fuel feed against knock until this rising and falling region has been traced, and the selector is then phased to the same position for No. 2 cylinder and the process repeated on this and on each of the remaining cylinders in turn. Assume, for example, that the mixture strength at the carburettor is greatest when No. 2 cylinder reaches maximum knock, and that it has to be reduced successively for Nos. 3, 4 and 1, then the distribution is such that No. 2 is weakest followed by increasing strength for Nos. 3, 4 and 1 in the order named.

It is not suggested that the above examples indicate the entire field of usefulness of the Strobophonometer, but they serve to show the wide range of applications and the type of information obtainable.

The Authors wish to express their thanks to the Directors of the Anglo-Persian Oil Co. for permission to publish the experimental data given, much of which was obtained in the Engine Research Laboratory of the Company.

Influence of Tetraethyl Lead on Knock Rating.

The following has been received from Dr. F. B. Thole and Mr. R. Stansfield :—

In the paper on Knock Rating by Hebl and Rendel, pages 187-196, results are given of an investigation of the anti-knock effect of lead tetraethyl on various gasolines, and it is shown that k (a constant representing curvature of the H.U.C.R./lead concentration graph), is substantially the same in every case.

It is suggested in the concluding remarks that this may have some fundamental significance.

While k may be constant for fuels tested in the E.35 engine, it is found to vary over a wide range for tests in the Armstrong engine. Thus its value was 0·865 and 0·888 for two blended gasolines of similar nature, but different initial anti-knock value, but for another gasoline (aviation) the value was only 0·529, and in a further example (straight run) was 0·710. The respective susceptibilities for the above fuels were 0·643, 0·289, 0·802 and 0·862.

How far the difference between these results and those given in the paper is due to the engine design, and how far to the gasolines is not known, but it is evident that the conclusion reached cannot be applied indiscriminately at present.

A further section of the paper deals with the effect of natural gasoline on lead susceptibility, and also on the more general effect of volatility. Tests made in the Armstrong engine with straight-run Persian gasoline, with the aviation cut from the same crude and with various blends with Persian natural gasoline, have all shown the reverse effect, *i.e.*, the lead susceptibility is decreased as the fuel becomes more volatile, or as natural gasoline is added.

These differences are known not to be due to the engine design, since they also hold when the gasolines are tested in an overhead valve engine such as the C.F.R. or the S.30.

ERRATA.

In the above paper the following corrections should be made :—

P. 187, last line, for $I = 8NK$ read $I = 8N^{k}$.

P. 189, equation 3, for $S = \frac{I}{N\ 0{\cdot}75}$ read $S = \frac{I}{{}_{N}\ 0{\cdot}75}$.

REVIEWS.

PETROLEUM IN THE UNITED STATES AND POSSESSIONS. By Ralph Arnold and William J. Kemnitzer. Harper & Bros., New York and London, 1931. Pp. xxi.+1052, 91 tables, 39 illustrations. Price 63s.

This publication is the most exhaustive account of the conditions and statistics of oil development in the United States that has so far been attempted. It is really of the nature of a book of reference and will be welcomed as such by all oil technologists on account of the wealth of reliable information brought together in convenient form.

It deals with the salient facts of the geology and development of each of the producing oilfields of the U.S.A. and reviews its history, geology, field technology, and economics. Each section is abundantly supplied with statistics and there is a review of the economic position and future possibilities. Finally and perhaps of greatest importance is the selected, but very complete, bibliography on each area.

As a compendium of useful information there is no doubt of the value of this new publication, but it will be something into which one will dive for information, rather than read for its absorbing interest and illumination. To the student of geology or drilling technique the book will be disappointing. Apart from a single and very excellent map in colours of the geology of the U.S.A. the exposition on the geology is completely devoid of illustrations. To those conversant with the geology of the oilfields of the U.S.A. it will bring no new ideas, and to the student who wishes to learn something of these matters it will bring little illumination. Maps and diagrams are essential to the inculcation of geological facts and ideas. For these no letterpress is an adequate substitute and without these the ideas conveyed are meaningless or distorted. Further it is curious that, in a treatise which aims apparently at facts rather than at what one might term the philosophy of the subject, there should be found a section so elusive and controversial as "Source Rocks and Origin." Something less of this and a more adequate treatment of structure would have added to the value of the publication.

Apart from this general criticism of the geological matter the reviewer gratefully recognises that in this volume there is much solid information which will be of great help to the oil technologists. V. C. ILLING.

THE PRINCIPLES AND PRACTICE OF GEOPHYSICAL PROSPECTING, BEING THE REPORT OF THE IMPERIAL GEOPHYSICAL EXPERIMENTAL SURVEY. Edited by A. B. Broughton Edge and T. H. Laby. Cambridge University Press, Cambridge, 1931. Pp. xiii.+372.

Early in 1928 there was commenced in Australia, under the joint auspices of the British Empire Marketing Board and the Commonwealth Government, an experimental investigation of the applicability of various geophysical methods to problems of economic geology. The work of this survey aimed primarily at testing methods, as suggested in the report of the Geophysical Sub-Committee of the Committee of Civil Research, published in 1927 by the Empire Marketing Board. Widely separated areas, carefully selected in the six Australian States, have been occupied and explored by the field parties, and the elegant and well-printed volume under review is the record of the results achieved during the two years the work lasted.

Although all the four principal geophysical methods were employed, the report reveals that the electrical method, embodying the various devices dependent upon differences of electrical conductivity, constituted the chief

work of the Survey. This was natural enough, for the Director, Mr. Broughton Edge, and the Deputy Director, Dr. Bieler, whose untimely death in July, 1929, was a most severe blow to the Survey, were both especially expert in this method. Moreover, the general nature of the problems which invited attack, and the rather inadequate equipment of the Survey in other respects, provided a definite bias to electrical prospecting. The result is that we have here certainly the most comprehensive statement in the English language of the theory and practice of electrical surveying, and probably the best extant. In this respect the Survey has most successfully achieved one of the principal objects for which it was instituted, namely, to provide "a full disclosure of the scientific facts hitherto kept as jealously guarded secrets."

In the other branches of the work of the Survey, for example, the gravitational investigations, the report cannot be regarded as so authoritative; still, here again, it is good to have full details regarding the behaviour of the instruments employed under the conditions of field work in Australia. Defects demonstrated always tend to lead to improvement.

Although the seismic work was not commenced until halfway through the Survey, and was considerably handicapped by insufficiency of instruments, encouraging results were obtained. The magnetic method also has been found to have important applications not at first contemplated.

The volume is arranged in two parts, the first giving in a preliminary way the essential principles of the various methods, but dealing mainly with the field procedure and the results obtained, concerning both of which a wealth of detail, not usually found in similar publications, is placed on record. In the second part we find fuller treatment of the theory of the methods and the instruments employed in them. This arrangement, although not always convenient for reference purposes, does enable the reader generally to select his reading according to his taste.

The Survey has sometimes met with failure, but it has had notable successes also, as proved by drillings on the basis of the geophysical indications. These successes may even be more numerous than is claimed, for some areas indicated have not yet been proved or otherwise by drilling, for economic reasons. On the whole, the Survey seems to have been definitely justified, more particularly as pointing to the types of future development which are desirable. It is distinctly unfortunate that the termination of the work and the publication of the report have come at this time of world economic depression. But their usefulness will doubtless be proved in the future revival which we may expect; for the Survey has demonstrated that, with due care in the selection of the methods, all of them give promise of valuable application to either mineral or structural geological problems in Australia, and, by implication, elsewhere in the Empire.

It remains to congratulate the contributors to the volume for their lucid treatment of the subjects, and the editors for their skill and care in arranging the matter in this handsome and readable book. A. O. Rankin.

Das Erdol seine Physik, Chemie, Geologie, Technologie und Sein Wirtschaftsbetrieb. Part 1, Volume III. Die Gewinnung des Erdöls durch Bohren (Dr. Karl Glinz) und Die Gewinnung des Erdöls durch Schachtbau (Bergwerksdirektor Gottfr. Scheiders). Edited by Dr. Jenö Tausz. Leipzig: Verlag von S. Hirzel. 1932. Pp. xii.+262. R.M. 40.

The book reviewed is one section of a revised edition of the well-known Engler-Höfer book, "Das Erdöls." It is the first part of the third volume, and deals with modern drilling and production tools and methods.

The chapters cover: Initial organisation of an oilfield, short survey of drilling methods, standardisation of equipment, etc., by the A.P.I., cable

tool drilling, the Canadian system of drilling, the rotary system, combination rigs and system, coring methods and tools, special drilling tools, cementing, flow control methods, swabbing, pumping, air and gas lift, water drive, re-pressuring, torpedoing, fishing, removing casing and abandoning a well, subsurface survey instruments, drilling reports, etc., and stores.

Practically no recognised method of drilling or process of producing oil gas escaped description in this volume although, in many instances, the accounts are brief. Special interest attaches to the work in consequence of the detailed references to European methods, which are so frequently treated with scant notice in most technical publications of U.S.A. origin. Admittedly, in the case of drilling procedure, this data has now little more than historical interest, as much of the elaborate equipment illustrated and described will very shortly be relegated to the scrap heap. European oilfield operators have always favoured Canadian and percussion flush methods until recent years, but they are steadily being displaced by the rotary methods based on American practice. For the use of students the matter must always prove useful and instructive as indicating the ways and means of combating trouble before the value of mud fluids was realised and prior to the introduction of metallic alloys and special steels. The many ingenious, expensive and freakish tools designed to overcome difficulties which are no longer experienced show clearly the patience and perseverence exercised to overcome troubles inseparable from former methods of operation.

Modern rotary equipment of American and Continental design is well illustrated, and reference is made to practically all recent refinements and innovations, such as the hydraulic feed types and Reed wire line bit. Rock and coring bits are described as well as the Russian turbo-rotary bit. An account of cementing processes is followed by a description of methods taken to control the flow of wells by back pressure with beans.

Under production methods will be found a description of air/gas lift, bailing, swabbing and pumping of wells.

Water-flooding and re-pressuring by air or gas are briefly discussed, and the surveying of wells receives attention. No less than 57 pages out of the 258 comprising the volume are devoted to the production of petroleum by mining, and this section shows a considerable amount of specialised knowledge.

The illustrations of plant, tools and apparatus are numerous and well chosen, and are generally good, notwithstanding that the paper is not very suitable for the photographic reproductions.

Throughout the book a lucid style is used, and the descriptive matter, although essentially technical and brief, is, in most cases, complete and to the point.

An extensive bibliography is given, but the index appears inadequate and brief. The volume may be regarded as a creditable addition to the number that form the complete set.

C. A. ANDREWS.

THE SCIENTIFIC PRINCIPLES OF PETROLEUM TECHNOLOGY. By Dr. Leo Gurwitsch and Harold Moore. Second Edition. London: Chapman and Hall, Ltd., 1932. Pp. 584. 30s.

The translation of Dr. Gurwitsch's book published in this country in 1926 is so well known to members of this Institution that this revised and amplified second edition needs no introduction, but only a further commendation.

When the present writer reviewed the first edition in 1926 he expressed the opinion that while the book did not live up to its title, in that it dealt with few scientific principles and still less technology, it was an admirable treatise on the chemistry of petroleum and its components. The new edition, while retaining all the valuable qualities implied in the latter phrase, has

gained materially by the addition by Mr. Moore of numerous sections, totalling about 100 pages, on the more technical side of the subject. The result is a much better balanced volume in which we find not only an admirable survey of the purely chemical and physical characteristics of the group of substances constituting petroleum, but also a clear explanation of the importance of these characteristics to the practical aspect of the production and utilisation of the refined products.

As in the original edition, the book is divided into five main section. These sections are :—

(1) The constituents of petroleum and the action of chemical reagents on them.
(2) The physical properties of the constituents of petroleum.
(3) The distillation of petroleum.
(4) The refining of petroleum products.
(5) The properties of the refined products.

The authors are to be congratulated on having refrained from the attempt to create a miniature "Das Erdol" and on having taken pains to consider, and if necessary to criticise, the data and opinions they quote.

The first sections deals mainly with the effect of chemical reagents on the hydrocarbons, while, as would be expected, the oxygen compounds so characteristic of Russian oil receive considerable and perhaps disproportionate attention. The chapter on sulphur has been expanded from the former 3 to 18 pages and includes a good bibliography, but this section still merits considerable development. Much important work on the chemistry of the mercaptans and their salts receives only a footnote reference and the names of Lachmann and Meyer are not even mentioned in this connection.

The section on physical properties is practically unchanged except for the addition of some paragraphs on transformer oils which had no place in the former edition.

The third section, which is also the first section of the "Manufacture portion of the book, deals very briefly with the theory of fractionation, touches on the refinery aspect of distillation and then passes rapidly to cracking, the chief processes being described. We cannot subscribe to Mr. Moore's statement, "It is as regards the high percentage of unsaturated bodies that the vapour phase processes are at a disadvantage against the liquid phase processes." With the obvious proviso regarding the elimination of the 1 or 2 per cent. of gum-forming compounds, the great merit of a vapour-spirit is its high olefinic content and consequent high octane value. Hydrogenation as applied to coal by Bergius and to oil by the Standard Oil Company of New Jersey is briefly touched upon.

Section four deals with the refining of petroleum distillates by chemical and physical means, and presents quite adequately the methods in general use.

The last section describes the principal products manufactured from petroleum. One can hardly expect to find much more than a summary within the limits of 56 pages, and the classic phrase, "What there was was good," instinctively comes to mind. It is rather distressing, however, to note the complete omission of any reference to Diesel fuels (distillate or residuum) or road bitumens in this section, when 14 pages are allotted to the relatively insignificant products wax and petroleum jelly.

This new edition is such a marked advance on the first that the reader can be strongly recommended to scrap his copy of the latter at once, and we look forward to the appearance in due course of a still further improved third edition.

F. B. Thole.

BOOKS RECEIVED.

DAMPFDRUCKE BINAERER GEMISCHE UND IHRE BEDEUTUNG FUER DIE ABSORPTION FLUECHTIGER STOFFE. By Dr. Ing. Luigi Piatti. Verlag von Ferdinand Enke, Stuttgart, 1931. Pp. 53. RM. 4.80.

Following a brief introduction, the author gives a summary of the various theories evolved to explain the behaviour of binary mixtures, after which he proceeds to deal at more length with the theories regarding the vapour pressures of these mixtures.

In Chapter IV. a historical survey is given of the technical development of the process of absorption of gases by liquids, whilst the various considerations are set forth which have to be taken into account when applying such a process. The conclusions arrived at are summarised at the end of the booklet.

The subject is dealt with in a popular style without introducing thermodynamics or mathematical deductions. Some graphs and numerical data, as also a fairly extensive bibliography, contribute towards making this booklet a useful introduction for anyone desiring to take up the study of this subject.

GEOPHYSICAL PROSPECTING, 1932. New York, Amer. Inst. Min. Metall. Eng., 1932. Pp. 510. $5.

Since the publication of the first volume of this series in 1929, papers on the subject of geophysical prospecting have accumulated, and twenty-four have been selected for publication in the present volume. Each paper deals with some aspect of the subject, and each author is actively engaged in the use or in the interpretation of geophysical methods. Apart from general papers and theoretical studies, the following methods are dealt with specifically, Resistivity, Electromagnetic, Magnetic, Seismic and Gravitational.

CHEMICAL ENGINEERING AND CHEMICAL CATALOGUE. 8th Edn., 1932. London: Leonard Hill, Ltd., 1932. 10s.

The eighth edition of this annual reference work follows the lines of the previous volumes. The main index has been translated into German, the Data and Tables Section has been extended, and the Bibliography has been entirely re-arranged. The classified Index of Manufacturers could be improved by the inclusion of a more complete list of manufacturers of oil refining plant, etc.

BIBLIOGRAPHY OF BIBLIOGRAPHIES ON CHEMISTRY AND CHEMICAL TECHNOLOGY. National Research Council, Washington, D.C., 1932. Pp. 150. $1.50.

Bulletin No. 86 of the National Research Council is the second supplement to the series of Bibliographies of Bibliographies and covers the period 1929–1931. The original Bulletin (No. 50) covered 1900–1924, and the first supplement (No. 71) 1924–1928. The price of No. 50 is $2.50, of No. 71 $1.50, and the complete set of the three Bulletins can be obtained for $4.00.

LEITFADEN DER TIEFBOHRTECHNIK. By Paul Stein. Verlag von Julius Springer, Berlin, 1932. Pp. 52.

The author states, in his preface, that this guide is intended for those already connected with deep drilling, students and laymen. It is a revision of two previous editions published in 1905 and 1913, and covers a wide field,

but brevity has been carried to excess in many instances. Diamond drilling is disposed of in two pages, whilst casing occupies barely one page. No attempt has been made to discuss in detail the problems connected with the technique of deep drilling, and the booklet serves more as an introduction to further study.

Among the subjects treated are Prospecting, Rotary, Cable Tools, Freefall Fauck, Fanville and Raky systems, Casing, Cementing, Fishing Jobs, Diamond Drilling and Coring. The information given, which is contained in 50 pages, is that generally accepted by oil technologists, but is so meagre that it is doubtful whether it can be of use to anyone not connected with the petroleum industry.

The booklet is well printed and the illustrations, fifty-eight in number, are extremely well done. A. W. NASH.

ERRATA.

P. 408, Line 20. For "Lander" read "Landa."